SIMULATION OF VEHICLE PERFORMANCE AND FUEL CONSUMPTION FOR FREE FLOW TRAFFIC

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

by
ASHOK KUMAR MISHRA

to the
DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

FEBRUARY, 1982

24.2.82

CERTIFICATE

This is to certify that the thesis 'SIMULATION OF VEHICLE PERFORMANCE AND FUEL CONSUMPTION FOR FREE FLOW TRAFFIC' submitted by Shri A.K. Mishra, in partial fulfilment of the requirements for the degree of Master of Technology at the Indian Institute of Technology, Kanpur has been carried out under my supervision and guidance. The work embodied in this thesis has not been submitted elsewhere for the award of a degree.

February, 1982

S.P. Palaniswamy

(Dr. S.P. PALANISWAMY)
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology, Kanpur

CE-1982-M-MIS-SIM

ACKNOWLEDGEMENTS

I feel extremely glad in expressing my profound and sincere gratitude to my thesis guide Dr. S.P. Palaniswamy for his highly inspiring and invaluable help rendered to me at all stages of the work.

I would also like to convey my sincere thanks to:

- Dr. B.R. Marwah
- Prof. C.S. Moorthy
- The faculty of civil engineering
- Works Manager - Kailash Motors
- Ramalingaiah
- P.S.R. K. Sudhakar, S.C. Mittal, S.P. Singh, K.K. Agrawal, P.K. Mittal, S.P. Namballa, Rahim, F.S. Umrigar, V.J. Kulkarni, Capt. C.P. Gupta, S.P. Pattnaik and my friends.
- And finally thanks to Mr. S.N. Pandey and Mr. G.S. Trivedi for their neat and prompt typing work.

A.K. MISHRA

ABSTRACT

Road transportation has grown at a rap dirate ompared to other modes in the past three decades. This rend witnessed in the past is expected to continue to operate in the near future. Road transportation accounts or a significant proportion of the total energy consumed in the transportation sector. The petroleum and other oil products used in road transportation are scarce commodities and their prices have been rising steadily since the beginning of energy crisis. Under these conditions it is imperative to explore the opportunities to conserve fuel consumption in the road transportation system. Within this framework it is considered that the roadway design parameters lend themselves as potential candidates in optimizing the energy use. The planner and designer do not have adequate inputs regarding the fuel consumption which will be a function of not only the quality of roadway elements but also how this fuel consumption varies with the increasing volume of traffic. This study attempts to bridge this gap partially by developing a simulation model for free flow traffic conditions. This model could be used to evaluate not only the performance of the vehicles but also enable us to estimate the fuel consumption. The various

submodels describing the vehicle, roadway and driver interaction have been developed which are used in the simulation of fuel consumption. Three types of Ashok Leyland models and the Ambassador Car have been simulated on a hypothetical 10 kilometre roadway. The resulting fuel consumption obtained for steady state as well as free flow conditions have been shown to represent the system behaviour adequately.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

1.1 Objective of the Study:

An analysis of the impacts of different energy policy options on energy conservation requires a clear understanding of the way in which traffic and transportation operating characteristics are converted to energy consumption. A systematic framework is not yet available to relate traffic and energy. Thus, to analyze the effects of conservation policy options in investment planning analysis this research attempts to develop a computer model to simulate the vehicle performance and to estimate the energy consumption of freemoving roadway vehicles. Road transportation, which accounts for a significant proportion of energy consumed in the transportation sector is an obvious candidate for attention and therefore we have chosen to deal with it in this study.

1.2 General:

Energy in one form or another enters practically every single economic activity and its availability and cost could decise the economic well being of the nation. Considerable work is being done on alternative sources of

energy all over the world, but it is still uncertain as to the areas where the major breakthroughs will occur and in what period of time, but it is quite certain that in next two or three decades pattern of energy generation and consumption will change. Till such time most of the economic activities have to depend upon the conventional sources of energy viz. coal and fossil fuels. Therefore it is imperative to plan for energy conservation and utilize the available energy in an optimal manner through engineering design of systems which are more energy efficient and operate them so as to minimize wastage of energy.

Energy conservation means reducing the amount of energy consumed to perform a service of given size and characteristics. Each mode in transportation sector can conserve energy by adopting new technologies, modifying operating procedures or a combination of both. Within the overall transportation sector, some energy conservation can be achieved by a shift of carefully selected traffic to less energy intensive modes. The government can affect the conservation process by introducing appropriate policy measures directed at the technology and operating characteristics of individual modes.

Transportation is the second largest commerical energy consuming sector and has accounted for about 30 percent of commercial energy consumption in the country. Energy consumption in this sector has been rising steadily at over 7 percent per year. At present about 12 million tonnes of oil is consumed in this sector which is about 60 percent of the total oil produced and imported [8].

Road transportation, in particular, heavily depends on diesel, petrol and other oil products for its operation. Road transportations share of the total passenger and freight movement in the intercity context are 66 and 33 percent respectively in terms of passenger-kilometres and tonne-kilometres which are the indices of productivity in this sector.

TABLE 1
TREND IN THE GROWTH OF TRANSPORT VEHICLES

Sl.No.	Type of Vehicle	Number of vehicles (in thousands)			
		1961	1970	1975	1977
1.	Passenger Cars	256	490	591	827
2.	Jeeps	32	78	93	
3.	Two wheelers	88	472	936	1334
4.	Three wheelers	6	31	75	
5.	Buses	57	92	100	117
6.	Trucks	168	322	334	367
7.	Tractors	31	133	202	NA
8.	Other vehicles	35	113	236	

Source: Report of the Working Group on Energy Policy, Planning Commission, New Delhi, 1979 [8].

While the steel wheels on steel rail reduces the rolling resistance to one fourth of what is encountered by the rubber tyres on concrete pavements there are factors which favour road transport which are of multi-dimensional nature. A balanced transportation development should consider various trade-offs among these factors which would be conditioned by socioeconomic aspirations, strategic needs, even development of regions and other political considerations. Road transportation being more suitable for dispersed economic activities will continue to grow unabated with the population growth and its needs.

The number of vehicles in use in road transportation from 1961 till 1977 is given in Table 1. Even though the number of automobiles is close to one million their operation is mainly confined to the urban areas. The ownership pattern and cost of the petrol have greatly affected their economic viability as a mode for intercity passenger transportation. The second category of vehicles namely two and three wheelers are again used predominantly in urban areas.

Trucks and buses account for about 80 percent of the rural automotive highway traffic. They are the largest consumers of road transportation energy. Trucks are mainly used for intercity freight movement, while buses are used

in urban as well as intercity passenger transportation. The growing use of trucks for freight transportation is due to improvements in the national highway network and the geographical expansion and distribution of industry, commerce and major human settlements. In addition trucks offer speedy delivery, flexibility in routing and sheduling, and door to door service. Because of these factors, trucks are particularly usefull for small shipment of high value and short hauls. Trucks dominate intercity freight transportation at distances less than 300 kilometres and even longer hauls are quite significant which trend is expected to continue in the future.

Rural highway traffic consists mostly of free moving vehicles. As we approach major urban settlements the traffic becomes more and more congested. Interaction of vehicles moving in single and intermediate lane highways are quite significant. Various vehicle categories operate over the rural highway network which aggravates free movement of traffic. It is therefore necessary to study the performance characteristics of these vehicles and simulate their movement under free moving conditions over the given roadway stretch and calculate the energy consumption for the purposes of evaluation of road improvement investment planning opportunities for conserving the energy in road transportation.

1.3 Energy Conservation Opportunities in Road Transportation:

Useful economies might be achieved in the several areas. In the short term, there may be important savings associated with improvements in driving techniques, traffic management and engine tuning. Benefits might also result from a greater use of existing technology, for example, electronic ignition systems and widespread use of radial-ply **tyres** . Looking into the future, the use of lighter vehicles with better aerodynamic design, the use of transmission systems designed to improve the match between the engine characteristics and road load requirements and finally a change to new, more efficient engine may all help to reduce the nations fuel consumption.

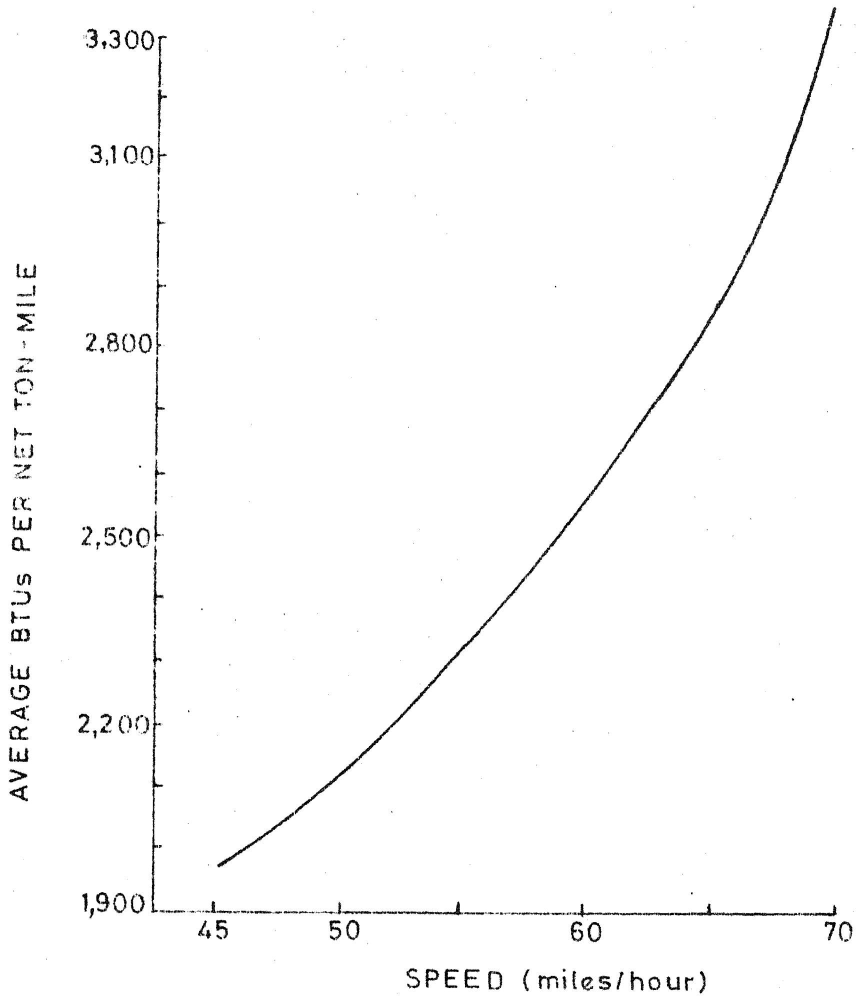
The factors which could result in energy conservation through operating changes include changes in capacity utilization, speed and fleet make up. For a given capacity utilization factor, fuel consumption will be greater if the proportion of empty kilometres is increased and load factor is correspondingly decreased. This is because fuel consumption increases at a marginally lower rate with increases in load, while back-haul fuel consumption varies directly with the number of empty vehicle kilometres. At low speeds, rolling resistance of vehicles is greater than air resistance. The air resistance increases as the square

of the velocity. As a general rule energy efficiency per tonne-kilometre increases with vehicle size. These would represent some of the untapped potential opportunities to increase energy efficiency of road transportation vehicles.

1.4 Effect of Operating Speed on Energy Consumption:

Resistive forces increase with increased speed. While the rolling resistance and mechanical resistance increase linearly the air resistance increases exponentially. Therefore for any distance travelled, the work (defined as the product of resistance times distance) required increases with increasing speed. The increamental energy consumed as speed increases is a function of energy efficiency, that is, the ability to convert potential chemical energy into useful work.

Figure 1 shows the relationship between average BTUs per ton-mile at different speeds for trucking fleet [5]. These relationships were developed by computing the average values for all commodities and all truck types. The figure illustrates that the amount of energy consumed in trucking increases with increased speed at an increasing rate. Thus at 55 miles per hour a 1 percent reduction in speed will be expected to yield a 0.877 percent reduction



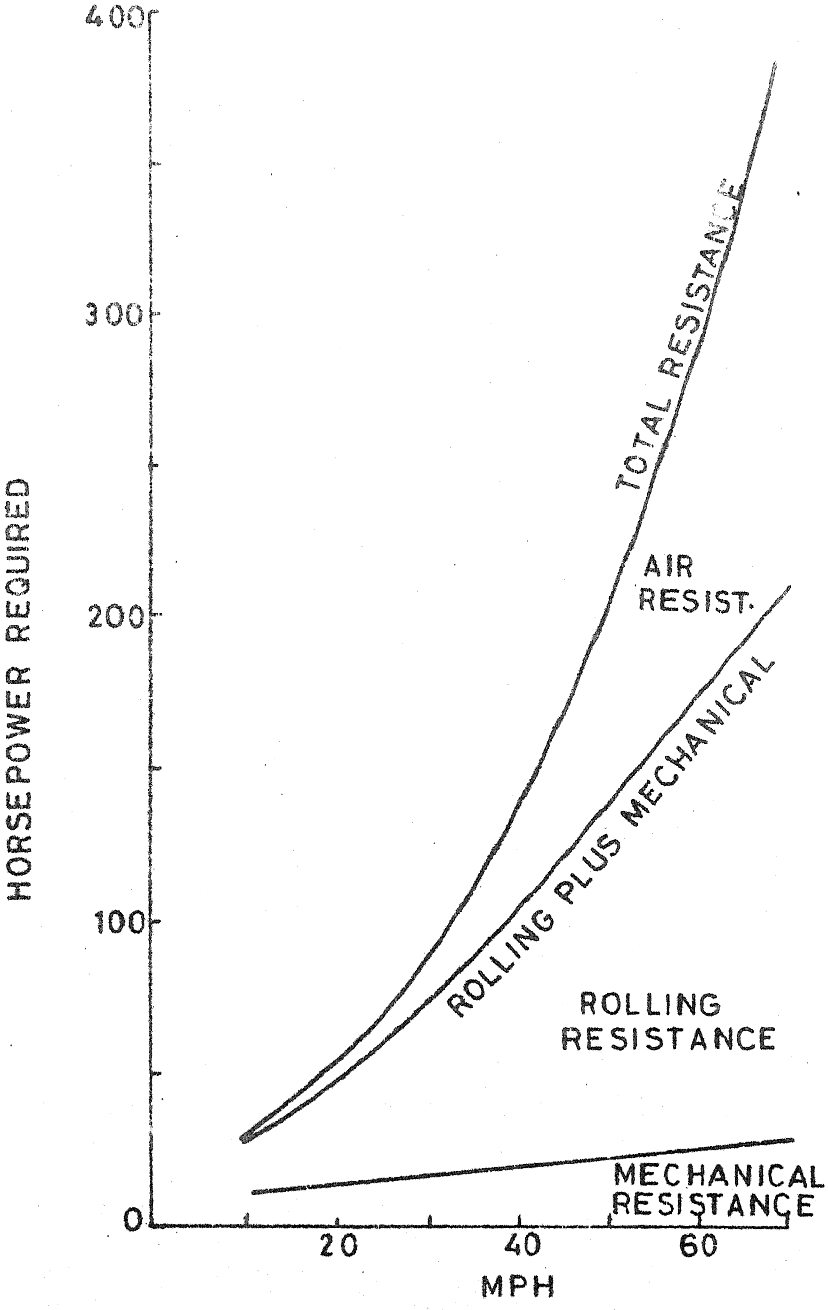
Source: Base on calculations from the TRANSEN model 1980

FIG. 1 ILLUSTRATION OF TRUCKS BTUS PER NET TON-MILE VERSUS SPEED AVERAGED FOR ALL COMMODITIES AND ALL OVER-THE ROAD TRUCKS

in fuel consumption, while a 1 percent increase in speed will result in approximately an 1.218 percent increase in fuel consumption.

Figure 2 illustrates the increasing energy requirements for higher speeds. The horse power required to overcome the different resistances to which trucks are subjected to increases with higher speeds. Figure 2 shows the cumulative requirement by type of resistance. Mechanical resistance (i.e., the internal friction of the engine and drive train) increases linearly with the speed. Rolling resistance (i.e., the friction of tyres on road surface) increases at a slightly greater rate with increasing speeds and, air resistance (i.e., the friction of air against the truck body mostly frontal area) increases at an increasing rate with speed. At low speeds rolling resistance is the greatest portion of total resistance. At 70 miles per hour air resistance is equal to rolling resistance for a large, fully loaded truck.

Changes in truck technology related to the engine, the drive train, and the vehicle itself are potential candidates for minimizing the energy consumption. Technological



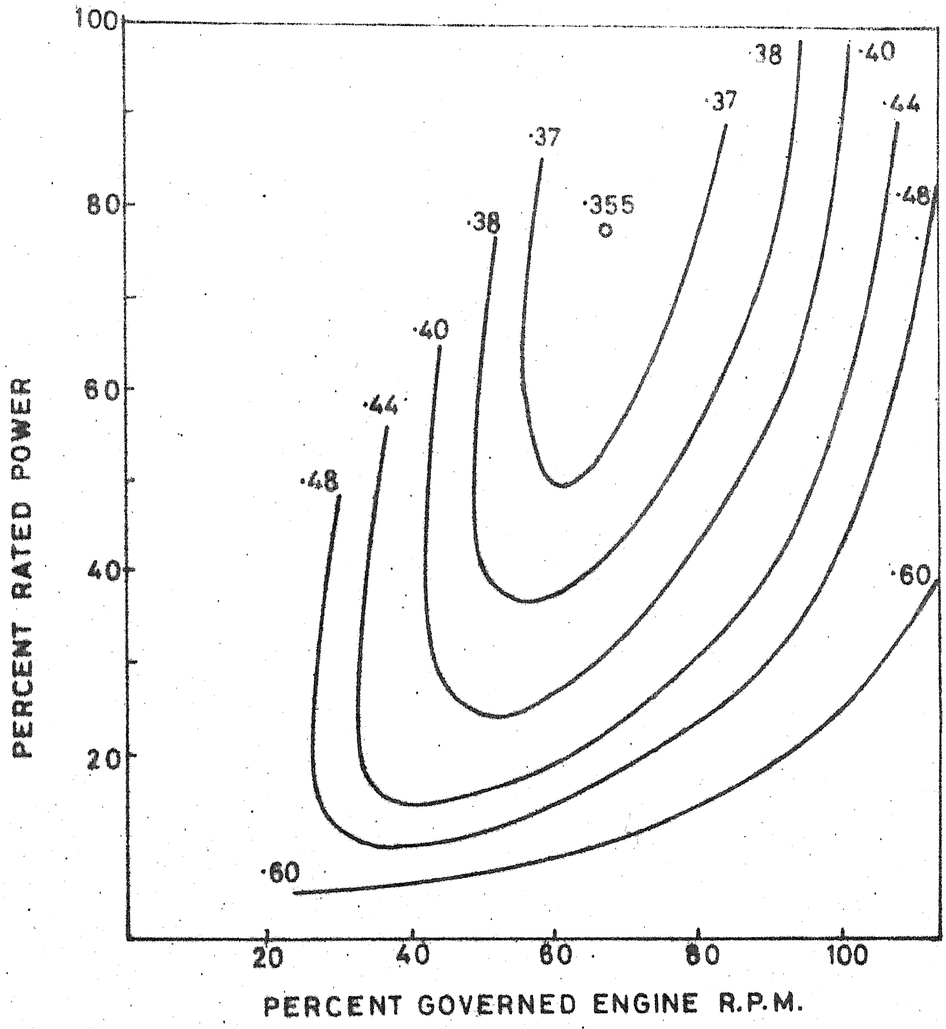
Source: Calculated from SAE Method J-688, Truck ability prediction

FIG. 2 TOTAL HORSEPOWER REQUIREMENT BY TYPE OF RESISTANCE AND SPEED

changes affect thermal efficiency, rolling resistance, air resistance, parasitic loads, and other sources of energy losses. The following paragraphs attempts to highlight some of the salient features related to energy consumption.

Engine optimization: As discussed above, slower speeds require less horse power, which in turn requires less fuel to move a given load a given distance. The relationship between engine horse power output and fuel input is not linear as indicated in Figure 3 . This graph shows fuel consumption curves for a typical supercharged diesel engine. The horizontal axis represents the governed engine speed in percentage. If this engine were derated the effect would be to lower the maximum governed engine speed without shifting the fuel consumption curves. The vertical axis represents the rated power which depends upon cubic displacement and the air intake capabilities of engine.

The problem of engine optimization is one of choosing an engine size which satisfies service requirements while operating at the lowest possible fuel consumption rate. Figure 3 shows a fairly wide range of horsepower and engine speeds near the optimum fuel consumption rate. The degree to which a particular operator can optimize will depend upon the consistency and predictability of his



SOURCE: CUMMINS DIESEL

FIG.3 TYPICAL FOUR CYCLE DIESEL ENGINE PERFORMANCE CHARACTERISTICS

operating conditions. If the vehicle operates most of the time at a given speed, over a given terrain, with a given load, the needed horse power can be computed. An engine can be chosen so that a needed horse power is 80 percent of the rated horse power and a cruising gear exists at 65 percent of governed maximum engine rpm. Thus, operation will be on the lowest specific fuel consumption curve (in this case, a point 0.355 lbs/brake-horsepower-hour). However if greater flexibility is needed to meet a variety of conditions then optimization will necessarily involve some trade-offs between fuel consumption and reserve horse power and speed.

Engine derating is a common suggestion to conserve fuel. Derating does not change the basic engine parameters that is, derating will not alter the fuel consumption curves in Figure 3 . It does, however, limit the amount of fuel charge which can be burned in each cylinder and engine rpm to less than 100 percent of maximum. Derating reduces the possibility of operating on a rpm/power curve with a high specific fuel consumption rate. Consequently, the maximum available horse power is decreased, the operator cannot go as fast, climb hills as quickly or accelerate at the same rate as with an engine governed in the conventional manner. The purpose therefore of engine derating is primarily to

involuntarily discipline the driver, since exactly the same effect can be achieved by careful use of throttle.

Derating, as a fuel saving measure, is not so much a technical as a behavioural relationship. The amount of saving will depend upon the prevailing behaviour of drivers.

Parasite Loads: Some accessories are driven directly from the drive train, such as water and fuel pumps, cooling fan, and alternator. Others are powered indirectly via electricity generated by the alternator. Horse power draw on the engine by accessory devices decreases the horse power available at the wheels. Significant saving can be realized from the use of thermostat cooling fan.

Drive Train Optimization: Engine optimization depends upon proper selection of gears. Many drivers due to inadequate training are not properly matching the transmission gear selection to engine characteristics. One improvement suggested is the introduction of automatic transmission in vehicles.

Aerodynamic Improvements: The most significant technological fuel efficiency measure is in streamlining the vehicles aerodynamically. Various modification can be made, such as, rounding the corners of vehicle, removing front bumper which reduces frontal area and adding airfoil which smoothens the flow.

1.5 Effect of Roadway Characteristics on Energy Consumption:

The above paragraphs dealt with the operational and technological options related to vehicles which are potential candidates for energy saving measures. One of the most important component in the highway transportation system is the roadway itself. Highways are to be planned and built to meet the demand in an optimal manner. Highway involve huge initial investments. High type facilities with ideal geometric standards would result in smooth flow of traffic and hence could reduce all operating costs to the user including energy. On the otherhand poor geometric standards result in the increased operating cost to the user. The road user and hence the economy in general is affected by the decision to adopt certain geometric standards for expected levels of future traffic. This aspect clearly brings out an important investment decision problem, which requires the consideration of trade offs between the initial investment and the road user costs which are incurred as vehicles are operated.

Currently the Central Road Research Institute,Delhi is engaged in the determination of various components of user cost as a function of the highway geometric and prevailing traffic flow conditions. There exist significant interactions between geometric features and traffic flow

characteristics under free flow as well as congested conditions which in turn affects the fuel consumption. The following paragraph attempts to focus the effect of roadway geometry on fuel consumption.

The vehicle operating on a roadway under free flow conditions tend to move with steady state velocities on geometrically homogeneous stretches. The steady state speeds adopted by drivers are what they desire for safe driving given the geometric characteristics such as lane and shoulder width and the riding quality of the shoulders, horizontal curvatures and gradients. Another important parameter is the pavement roughness which governs the steady state speed. Generally this speed will depend upon vehicle as well as driver characteristics. We call this speed as the desired speeds of vehicles over a given homogeneous stretch of a highway. As can be expected the desired speed will vary with the geometric features. An ideal geometry is expected to allow the driver vehicle combination under free flow condition to travel at a speed known as the basic desired speed. The desired speed is thus the effect of attenuation of the basic desired speed due to purely geometric parameters. A wide variety of vehicles are operated on our highways and their basic desired speeds are reduced considerably due to traffic interaction. This interaction becomes more and more significant as the pavement width narrows from the ideal two lane (7m wide) to single lane which is 3.8 m wide.

The single lane roadway causes severe impedances to traffic in the passing as well as crossing manoeuvres. The operating speed reduces considerably even for smaller volume of traffic. These situations result in significant energy consumption and must be carefully studied before these highways are selected for improvements.

1.6 Acceleration Noise and its Effect on Energy Consumption:

It is reasonable to assume that a driver will attempt conciously or unconciously to maintain a uniform velocity when he is travelling along an open roadway in the absence of other traffic. But he never quite succeeds. Even at low volumes on high type highway facilities he will fluctuate from his desired speed. When traffic interaction becomes significant the fluctuation about his desired speed will be more pronounced. His acceleration pattern, as a function of time has a random appearance. An acceleration distribution function can be easily obtained from such a pattern. This distribution is essentially normal. The random component of the acceleration pattern is called acceleration noise.

A measure of smoothness or jerkiness of the driving is then given by the dispersion σ of the acceleration noise. The mathematical definition of this quantity, assuming mean acceleration to be zero, is

$$\sigma = \left\{ \frac{1}{T} \int_0^T |a(t)|^2 \, dt \right\}^{1/2} \qquad (1.1)$$

in which $a(t)$ is the acceleration at time t and T is the total running time. Alternatively, if one considers that the acceleration is sampled at successive time intervals, Δt, then,

$$\sigma = \left\{ \frac{1}{T} \Sigma \left| a(t) \right|^2 \Delta t \right\}^{1/2} \qquad (1.2)$$

The dispersion, or standard deviation, σ, is simply the root mean square of the acceleration, and it has the dimensions of acceleration. Its values are usually quoted in $m/sec.^2$ or as a fraction or multiple of g, acceleration due to gravity.

Runs made on a section of the General Motors test track (on almost perfect roadbed) by four operators while driving in the range of 30 to 100 Kmph yielded normal acceleration noise distributions with standard deviates of 0.01 g $\pm$ 0.002 g. This dispersion has been found to increase at extreme speeds greater than 80 Kmph or less than 30 Kmph [1].

The acceleration noise of a driver will vary considerably as he drives on different roads or under different physiological or psychological conditions. A smooth trip will have minor deviations, a rough trip greater deviations from the mean acceleration.

The acceleration noise is mainly influenced by three factors- the drivers, the road and traffic conditions. Drivers who are aggressive go through frequent speed change cycles and they will have greater noise than the passive driver. Also more frequent speed changes are expected on a narrow and winding road as compared to high type facilities. Finally a driver in congested traffic will generate more acceleration noise than that obtained in low traffic volumes. Therefore acceleration noise can be used to evaluate various road geometries.

What is important to note in the acceleration noise is that it affects the fuel consumption of vehicles. There should be a definitive relationship between the acceleration noise and the fuel consumption. During a speed change cycle the excess fuel consumption over that of the steady state fuel consumption is due to the acceleration resistance to be overcome by the vehicle from the lower speed to the higher speed. Therefore the higher the noise the more is the excess fuel consumption. By carefully studying the acceleration noise and its effect on fuel consumption we could identify roadway design parameters which could be controlled in achieving the goal of energy conservation.

1.7 Scope of Study:

We have explored the possible avenues where changes could effect energy conservation in road transportation.

The vehicle offers significant opportunities which normally should be studied by the automotive engineers. In this study we consider the vehicles as given with certain performance characteristics. We simulate the movement of vehicles to study the effect of various roadway design parameters. It is believed that the transportation engineer can contribute significantly for highway facility planning and design by acquiring better understanding of the changes in road user costs brought about by the design parameters.

In this study we consider only the free moving road traffic. The interaction effect which is present on rural highways has not been taken into account. We emphasize that the study of interaction is an important area of research which should be persued further. Free moving traffic simulation has been thought of as the first step in the analysis of the fuel consumption which could shed enough light for further study of traffic interaction. A major benefit of this research is to enable us in understanding the interaction of roadway and driver vehicle system. An understanding of the vehicle performance on various roadways is the other objective of this study. The following section deals with the proposed study methodology.

1.8 Study Methodology:

The study of the vehicle performance and determination of their fuel consumption while moving on a highway is quite

complex in nature. A limited number of models have been suggested by those who are working in this field which do not provide adequate guidance. The main objective of this study is therefore to develop a model to predict energy consumption and thereby aid the planner and designer. This study attempts to develop the flow logic of free moving vehicles over the given roadway. The traffic system and dynamics of motion are captured through various submodels which are used to simulate the free moving trajectories and to calculate the corresponding fuel consumption. The vehicle characteristics, route characteristics, and the driver characteristics are incorporated in the submodels which mimic the real world.

Data on engine and other vehicle parameters have been obtained for three models of Ashok Leyland and for Mark IV of Hindustan Motors (Ambassador Car). A ten kilometres hypothetical roadway stretch has been used to simulate the movement of these vehicles. Rolling resistance of the roadway has been varied to study the effect of differing pavement conditions. The payload of the Ashok Leyland vehicles has been varied to obtain their transport productivities.

Fuel consumptions estimates have been made for both steady state as well as varying speed conditions. Gradeability and

acceleration capabilities of the vehicles at various speeds have also been obtained. The results of the simulation model have been quite encouraging.

1.9 Organisation of the Thesis:

The following chapter of this report deals with the literature review of the past work attempted in this field. As can be seen there are only a few papers in published form and remaining are still in the developmental stages.

In chapter three we attempt to develop detailed simulation logic for the various submodels. These submodels are : 1) acceleration cycle , 2) deceleration cycle 3) steady state flow, 4) gearshift process and 5) driver decision perception time model. Flow charts of these submodels are given along with the logic and assumptions behind these models.

A case study has been attempted in the last chapter by using the vehicle data for three models of Ashok Leyland and the Ambassador Car. Vehicle performance and fuel consumption have been obtained for these vehicles by simulating their movement over the hypothetical roadway. The salient conclusions and recommendations for further work in the lines of this study have also been presented.

CHAPTER II

LITERATURE SURVEY

Vehicle performance evaluation and fuel consumption calculations have been carried out mostly by automotive engineers for steady state and simple transient conditions. However, for complex conditions a more realistic model is required to represent the response of the vehicle and the driver to changing situations not only under free flow conditions but also when interaction effects due to traffic is significant. In simple models the driving of the vehicle along a given route has been represented by a finite number of steps or integrations. The fuel consumption has been investigated in this way by computer simulation in the United States [6]. Most of these studies have concentrated their attention on the application of computer simulation in the field of transmission matching, deciding on the best gear box, back axle and engine configuration for a given vehicle. The power plant concerned includes both diesel and petrol engines. The following paragraphs review the salient work which has been carried out in the past.

Vehicle performance and corresponding fuel consumption calculations were formerly made by using the

basic force equations for the given vehicle, driver, and roadway combination. Earlier attempts were of manual calculations. This yielded very limited information to the designer because it was difficult to incorporate the dynamics of traffic flow over long stretches of highways having varying geometric features. The advent of digital computer has made it practical to make extensive performance calculations at a low cost and time. The earliest of the studies in the analysis of vehicle performance and fuel consumption was the work by the General Motors Corporation [6]. The emphasis was on evaluating heavy truck performance on grades. Vehicle performance data such as the power output vs engine rpm and specific fuel consumption in addition to drive train data were collected and used in solving the force equation for the desired performance conditions. The vehicle was tested on a route having a series of variable length grades. The performance equations provided information about the vehicle motion at any instance. The equations were solved for increments of vehicle motion. The accumulated performance over the grades were then used to assess the gradeability of the trucks.

Gravem [3] has developed a fuel consumption model for road vehicles in connection with simulation of network traffic flow. He has calculated the fuel consumption for different vehicles during steady state speed, accelerations or decelerations using the equations of motion. This model is microscopic in nature in the sense that fuel consumption is calculated for every single vehicle, and is updated when there is change in the vehicle status, that is when an event occured. Following are the equations describing his calculations for fuel consumption analysis. The fuel consumption (FC) in a time interval (ΔT) is given by one of the following equations:

$$\text{Fuel} = \frac{SFC \times HP \times \Delta T}{3600} \qquad (2.1)$$

$$\text{Fuel} = f(V, \text{ grade Acceleration/Deceleration}) \qquad (2.2)$$

$$\text{Fuel} = 0 \quad \text{When the drive line is switched off.} \qquad (2.3)$$

Where SFC=specific fuel consumption in litres/hr-hp.

HP = horse power used

ΔT = time taken in seconds between consecutive events

Fuel = fuel consumption in litres

V = speed of vehicle in Kmph.

The remaining equations used in the model is the classical force equation alongwith resistance force values of vehicles when it travels on a roadway with the given geometry. For calculating the fuel consumption for private cars he has used the engine diagram in order to get the power output required in the process of doing the work in overcoming the road resistances. In the case of trucks normally operated in most of the European countries there are numerous gears and hence he has assumed that the truck drivers being professional in nature they always use approximately optimal engine speed and hence the constant specific fuel consumption. This is quite contrary to the situation prevailing in India where the trucks have limited number of gears. The above assumption considerably has simplified the fuel consumption calculations for truck categories of vehicles. In the case of cars his algorithm for calculating fuel consumption in a given time interval (Δt) given the speed and acceleration/deceleration is given below.

STEP 1

The power output is calculated for overcoming the resistance on the road including acceleration, if any.

STEP 2

If the power output is greater than a fixed amount, P_{min}, then engine diagram is used where fuel consumption is computed as a function of gear combination and engine speed.

STEP 3

If power output is less than P_{min}, engine diagram is not used. This situation could occur, for example, while travelling down the hilly terrain.

Under the conditions when power output is less than P_{min} he has used a modified idling fuel consumption corresponding to Equation (2.2). The fuel consumptions in this case will be a function of speed, gradient and acceleration/deceleration. Equation (2.3) will be used for fuel consumption if we cutoff the power transmission by switching off the engine.

Gynnersted et al. [2] have used an approach which is very similar to that of Gravem. They have assumed that the truck drivers use optimal power required in the fuel consumption calculations. However, for passenger cars

they have proposed a modification in the calculation of the actual power that the driver is using at the wheels as compared to the maximum power that the engine is capable of producing

They employ a transformation which is called 'drossel curve'. They define the ratio between used power and the maximal power as 'dellost' (d). This ratio 'd' is given as an 'outer dellost' (dy) and the inner dellost (di) where

$$dy = \frac{\text{Power at the wheels}}{\text{Maximal power at the wheels}}$$

$$di = \frac{P_i}{P_{maxe}}$$

Where P_i is the shaft horse power produced by the engine less all power consumed by auxiliaries.

P_{maxe} is maximal power at the engine.

Where di has been obtained as a quadratic function of the form

$$di = CO + C_1\, dy + C_2\, (dy)^2 \qquad (2.4)$$

where CO, C_1, C_2 are coefficient obtained in calibration procedure.

M.A. Renouf [7] in his study of fuel consumption of heavy goods vehicle used computer simulation and has validated the same. In his simulation he has considered the effects of various geometric features of roadway but has not considered traffic interaction. He reports that it was difficult to define the fuel used in small undulating sections due to many interacting factors. However he concludes that if most of the drivers will allow speed to increase downhill it is possible to get good overall agreement between simulation and experimental results. Cornering forces made only a small contribution to the overall fuel consumption on the test track of the Transport and Road Research Laboratory, UK, where there were significant curves, they accounted for 3 percent of the fuel used at the driving wheels unladen and 9 percent fully laden.

Other notable fuel consumption studies include that of Williams [10] who studied in great detail for parameters of tyres affecting the fuel consumption. Some of the factors considered have been the increase in the tyre inflation pressure, change from crossply to radial ply tyre, increase in tyre temperature and the change in the tyre

tread depth. He concluded that the rolling resistance coefficient increases as the inflation pressure decreases and the change in the rolling resistance coefficient with load are small. Tyre constructional differences can reduce the rolling resistance coefficient with the radial ply tyre having less drag than either the bias ply or cross ply tyre. An instrumented vehicle has been developed by the Transport and Road Research Laboratory, U.K. for studying the fuel consumption on a wide variety of roadways ranging from motorways to heavily congested urban roads [11]. The instrumented vehicle was primarily used to investigate the effects of traffic management on fuel consumption.

Williams reports energy losses in heavy commercial vehicles due to various factors concerning the vehicle and the roadway based on experimental runs of a Volvo truck with 8' x 8' container [9]. He studied the effects of cornering, and gradient in addition to the previously mentioned factors. Gyenes studied the fuel utilization of articulated vehicles and the effect of power train choice [4]. Power train parameter which were investigated included engine capacity, and engine torque-speed characteristic and

drive ratio. Fuel utilization was shown to improve as engine capacity was reduced. A detailed review of the past research has indicated the need for a simulation model which would not only predict the vehicle performance but also enable us to investigate the fuel consumption as effected by various roadway parameters under both free flow as well as congested conditions. The available literature do not provide adequate guidance for the roadway designer in terms of fuel consumption estimates. Therefore it has been felt that an effort should be made to develop a simulation model for freeflow traffic as a first step in meeting the requirements of the designer in this respect. The following chapter attempts to investigate the fuel consumption by structuring models to depict the various components and interactions among them.

CHAPTER III

SIMULATION MODEL FOR FREE FLOW TRAFFIC

A computer simulation model has been proposed which attempts to represent the way in which a driver moves his vehicle on a given roadway under free flow conditions. Procedure for calculation of fuel consumption has been presented within the framework of the simulation model. In order to simplify the model structure we have considered the system made up of mainly three components namely 1) vehicle characteristics 2) route characteristics and 3) driver characteristics. The representation of these components is kept as simple as possible. The following sections describe the characteristics of these components and flow logic for moving the vehicle driver combination.

3.1 Vehicle Characteristics:

In order to obtain the fuel consumption for a vehicle moving on a given route we simulate vehicle operations over various sections of this roadway. Since fuel consumption depends upon the operating characteristics

of vehicles we have to represent the various vehicle components in the model. Figure 4 shows the fuel flow from the tank in which it is converted into tractive effort and applied at the wheels to overcome various components of the road load namely rolling, air, grade, cornering, and acceleration resistive forces.

The internal combustion engine converts the chemical energy of the fuel into usable mechanical energy. In the process of thermal conversion in the engine there are certain losses due to poor burning in the comburstion chamber and the resulting power available is measured in terms of brake horse power . A part of this power is used to drive auxiliaries such as cooling fan, dynamo, and fuel pump. The net power available for overcoming the road resistances is thus reduced by the auxiliaries and should be accounted for in the fuel consumption calculations. A drive train mechanism consisting of reduction gears in gearbox and rear axle transmits power to the wheels. Losses also occur during the process of power transmission through this drive train mechanism.

The engine characteristics are defined by data in the form of an 'engine map'. Engine maps of various

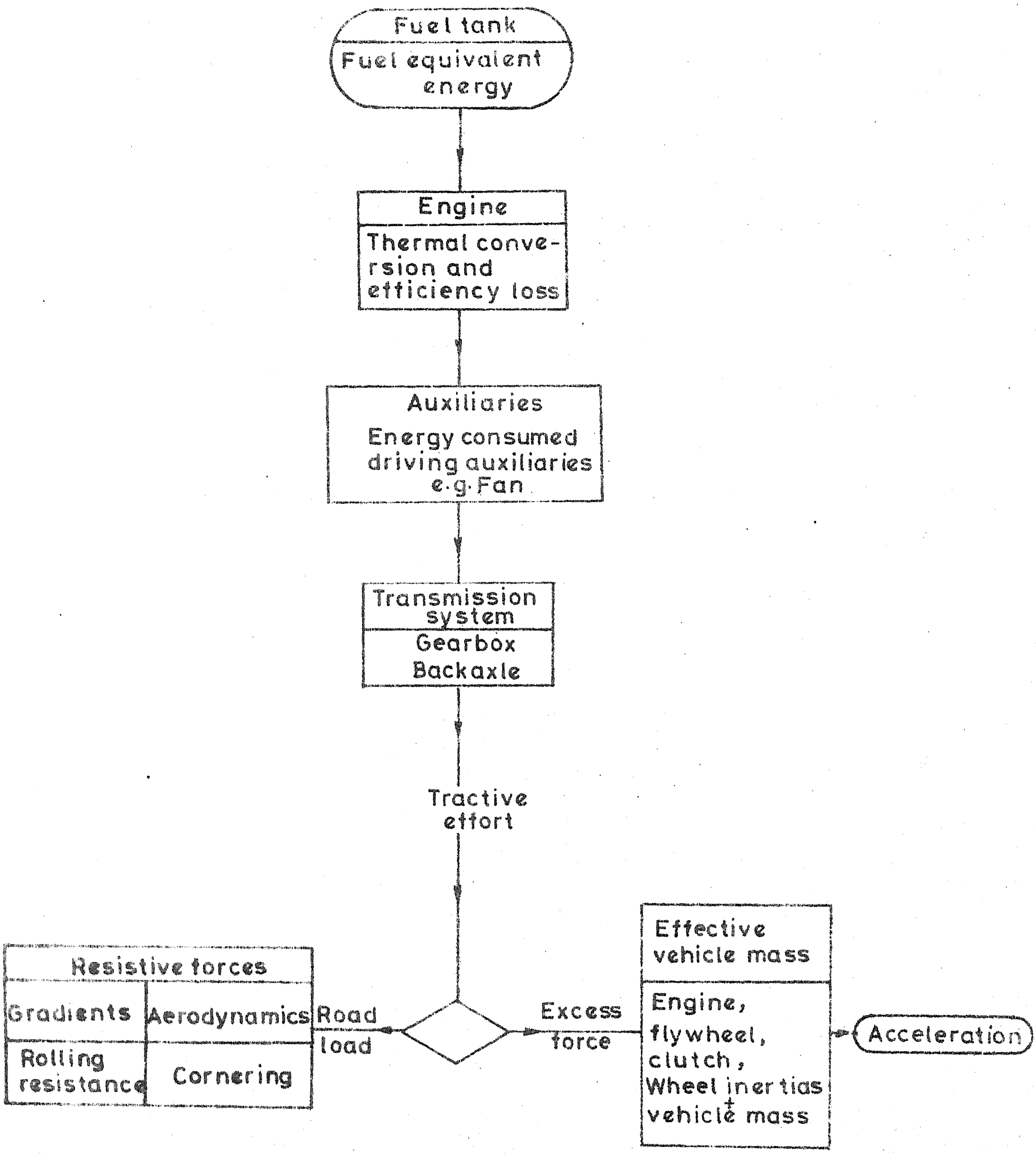


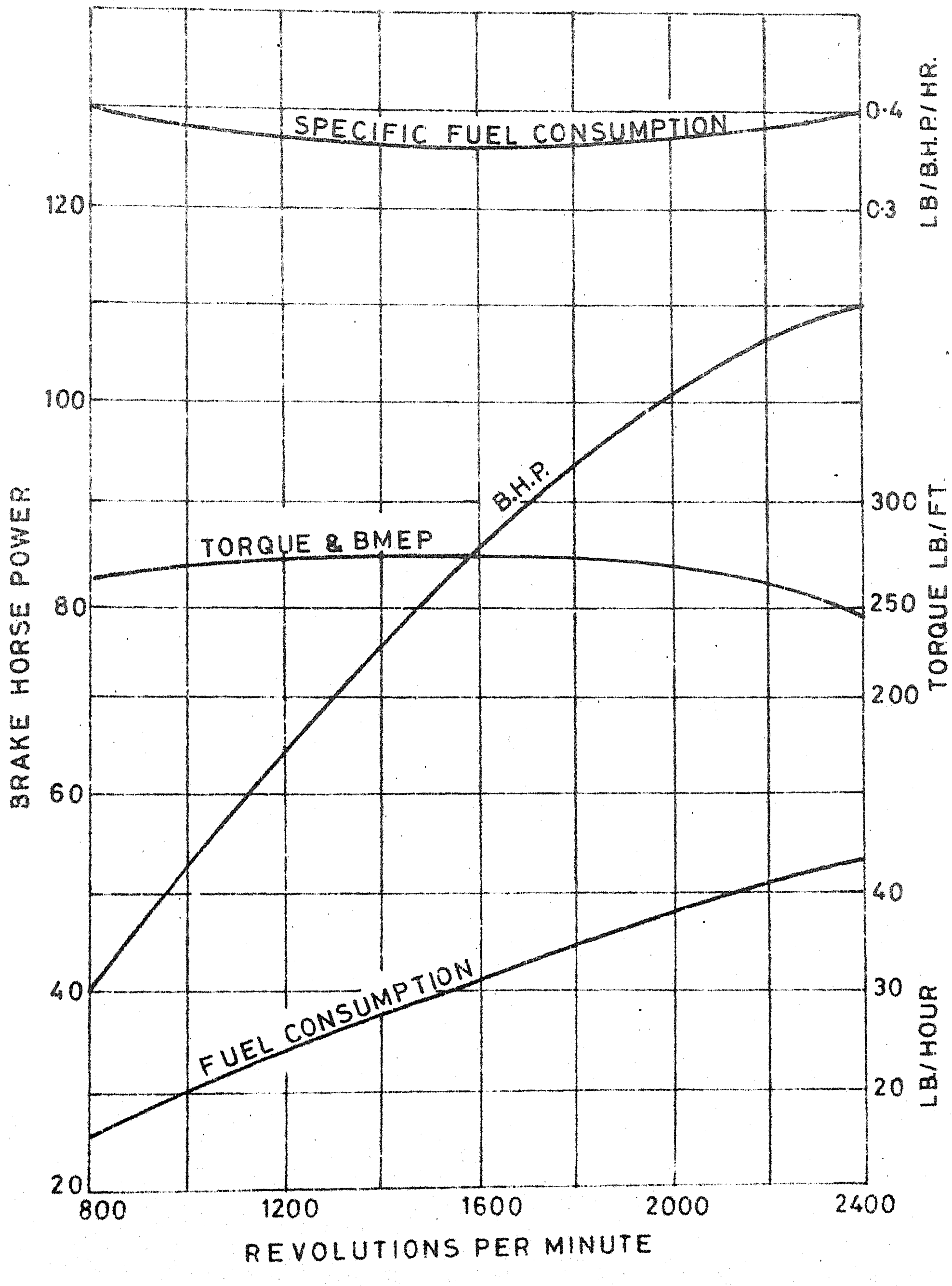
FIG. 4 ENERGY FLOW THROUGH THE ACCELERATING ENGINE

forms can be utilized but they all specify torque or a parameter proportional to it, and specific fuel consumption for a given engine speed (see Figures 5 and 6 on page 36 and 37). The specific fuel consumption is a measure of the engine efficiency. The smaller the amount of fuel consumed for a given output the more efficient is the engine. Usually the specific fuel consumption is expressed in quantity of fuel consumed per hour for the output of one horse power.

The road load which is the sum of all forces resisting the motion can be considered in the form of factors dependent on route as well as vehicle parameters. The aerodynamics depends upon the vehicle shape and its exposed area and the drag is determined by its speed and wind velocity over the route. In the simplest case only the frontal area of the vehicle and a single drag coefficient have been used.

If the tractive force applied to the driving wheels on a level road exceeds the road load then the vehicle will accelerate. Once the vehicle starts accelerating, the rotating parts in the coupled engine and transmission

PERFORMANCE DATA
ASHOK LEYLAND POWER PLUS TYPE 370 DIESEL ENGINE

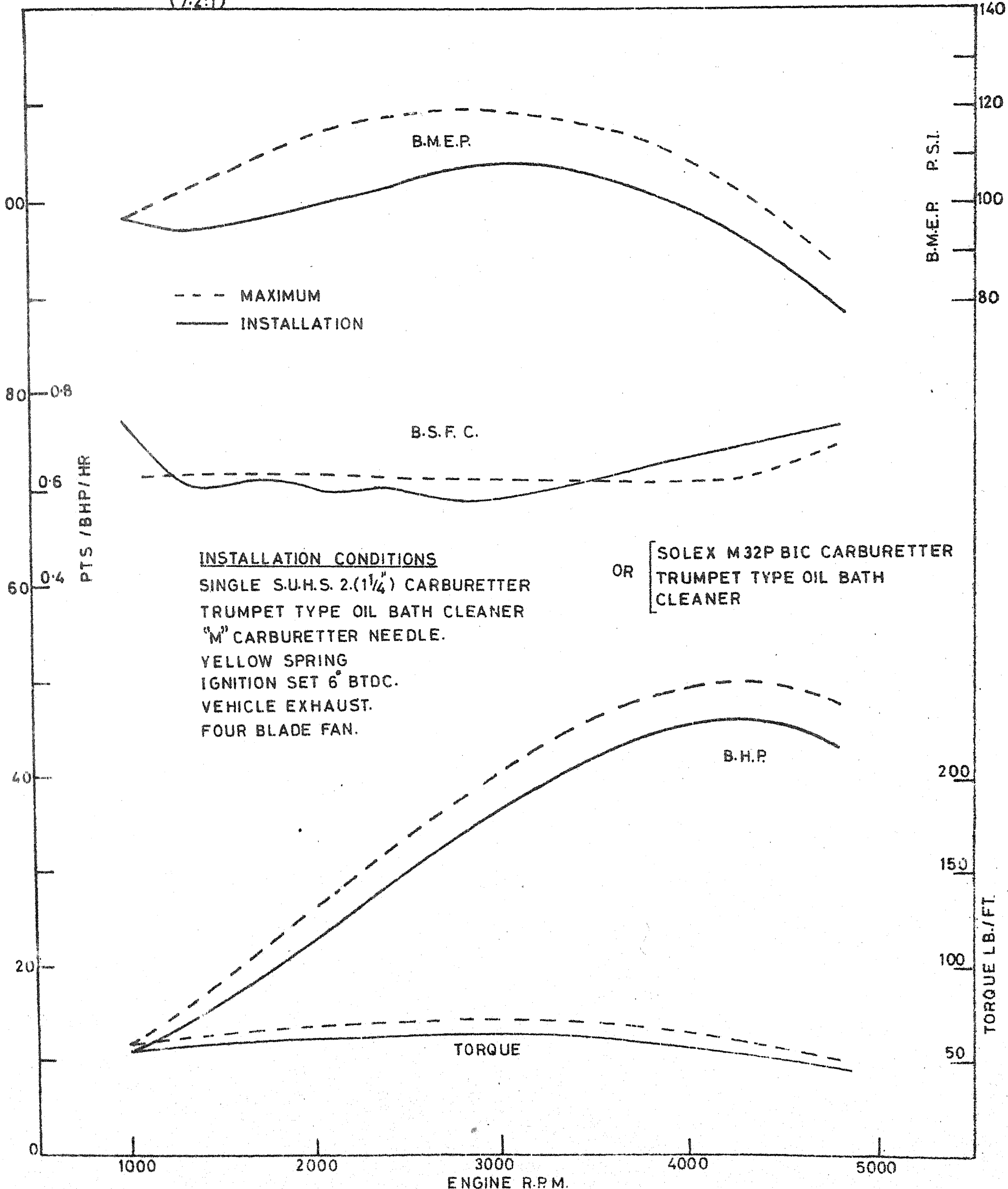


HINDUSTAN MOTORS LTD.

ENGINEERING DIVISION

ENGINE TYPE: 1500 C.C.
LOW COMPRESSION ENGINE
(7.2:1)

DATE: 6th Sept. 1956



system will also accelerate. Thus the mass of vehicle to be accelerated will be effectively increased.

3.2 Route Characteristics:

A route is represented in the model as an ordered set of geometrically homogeneous road blocks whose coordinates are specified. For each of these blocks we post a safe speed limit which incorporates the prevailing sight distance restrictions of the roadway. The acceleration and deceleration submodels describe the behaviour of driver-vehicle movement while speed changes occur. A higher required speed than the current will cause the vehicle to accelerate or to cruise at a speed close to it as far as possible . If a new required speed is lower than the current speed then the vehicle would slow down according to a predefined deceleration rate. Delays can be introduced as required, by the specification of idling time at stop.

A major factor affecting the operating condition of a vehicle is the route gradient. This can be defined as a distance at which a particular gradient begins or more usually by a series of heights from which

gradients are calculated. The start of a bend is specified in a similar manner as a radius of curvature which lasts until another is defined. The cornering force increases the observed rolling resistance encountered while on the bend and is a function of vehicle speed, weight , the average cornering stiffness and the radius of curvature.

3.3 Driver Characteristics:

In the simulation model driver is represented by the use of accelerator and the selection of gears which decide the driver controlled performance of the vehicle. Assuming the vehicle starts from rest then first usable gear is selected and the speed is increased by a set increment. The basic step carried out is the change of speed by this increment. A minimum power output is assumed in the very slow speed region.

A gear change is required when the prespecified speed for that gear is reached. During the gear change the transmission is disconnected and the vehicle coasts

till the gear is changed. An upward gear change is made if the speed in the new gear can be maintained and the engine speed would fall into defined operating range. Acceleration takes place using all or part of the torque available from the engine. The driver will try to attain the desired speed by changing gears when necessary. However, it may not be possible to reach the speed on occassions, for example, when a heavily loaded vehicle moving on a steep hill.

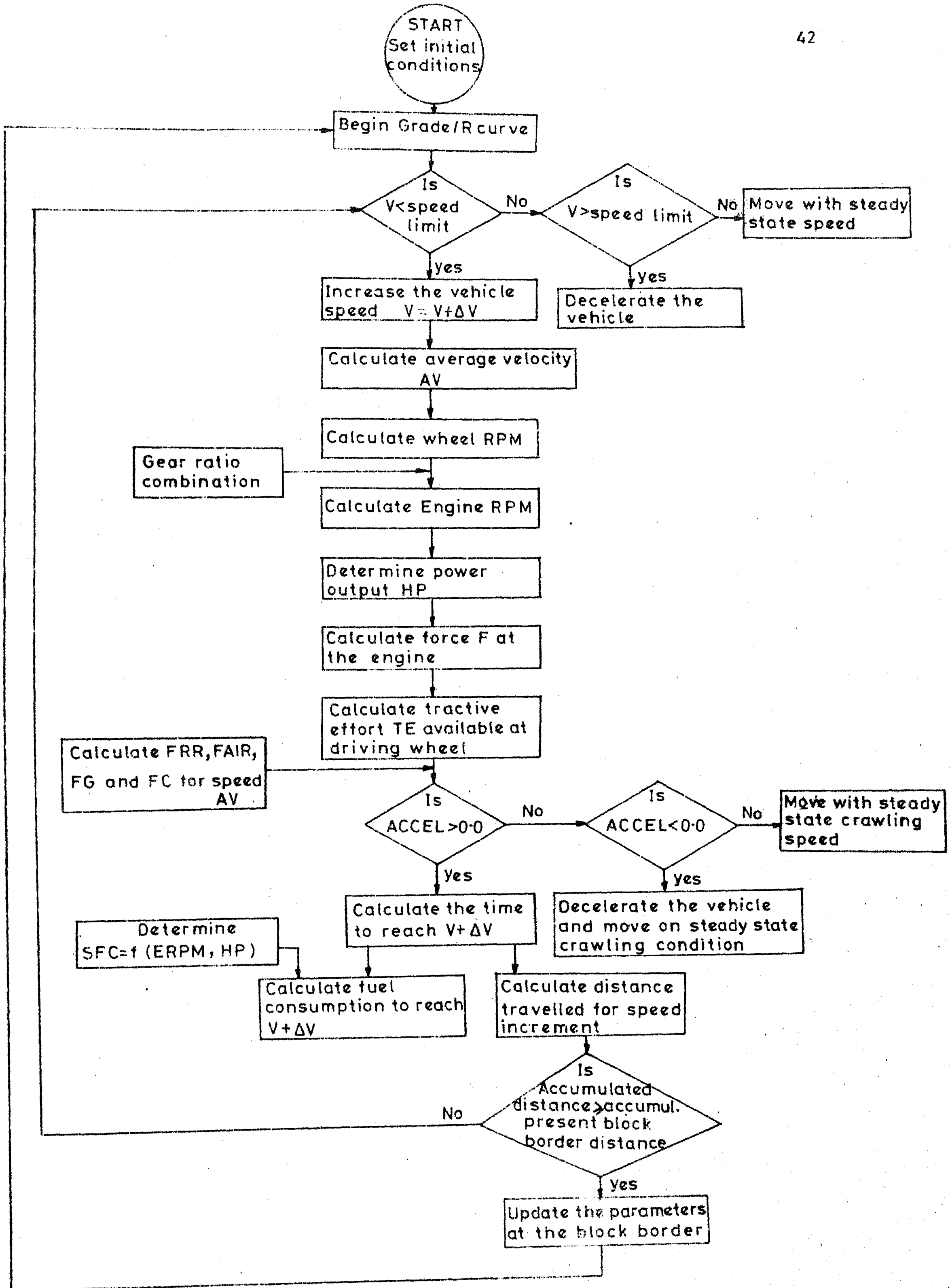
The following are the salient steps of computer algorithm developed in this study which simulates the time space trajectories of free moving vehicles. The driver behaviour is considered in his response to the various roadway elements which he has to take cognizance of in driving his vehicle in a safe manner. The algorithm proposed here consists of mainly five submodels namely 1) acceleration cycle in which a vehicle accelerates to reach a steady state condition, 2) deceleration cycle in which a vehicle decelerates from a higher speed to a lower speed to maintain either speed limit or safe driving conditions which is expected, for example,

when a vehicle encounters a sharp horizontal curve. 3) steady state cycle in which a vehicle moves at a uniform speed, 4) gear change process while vehicle reaches the prespecified gearshift speed and 5) driver decision perception time submodel. The following sections describesbriefly the logic of various submodels used in the simulation.

3.4 Acceleration Submodel:

Suppose that the vehicles starts from rest. We set the initial conditions for the status of vehicle at zero level. We start the engine with idle rpm and the corresponding power. Since the vehicle is in the neutral gear no power is transmitted to the wheels. The transmission line is engaged by selecting the first gear. When the vehicle starts moving it is assumed for computational purposes that the full throttle is applied by the driver. The vehicle will accelerate to gain speed. The vehicle status is calculated at speed increment of 0.5 kmph which has been chosen arbitrarily (see Figure 7).

Using the driving wheel circumference overall reduction gear ratio RED(N), (i.e. rear axle ratio



FIG· 7 ACCELERATION SUBMODEL

x-ratio corresponding to the gear number), and the average velocity, AV, of the vehicle over the speed increment we obtain the required engine rpm from the following equation

$$AV = \frac{ERPM \times 60}{RED(N) \times TYRE} \qquad (3.1)$$

where

TYRE = number of tyre revolutions per kilometer

ERPM = average engine revolutions per minute over the speed increment.

Corresponding to this ERPM thus calculated by using Equation (3.1) we proceed to determine the horse power delivered at the shaft which can be converted into force to be delivered at the wheels

$$F = \frac{HP \times 273.75}{AV} \qquad (3.2)$$

where

HP = horse power output at the shaft for the given ERPM

F = force in Kg.

The tractive effort (TE) available at the wheels can be obtained by subtracting the losses in the auxiliaries and drive train mechanism F(LOSS) (See Figure 8). This tractive effort is used to move the vehicle in overcoming the road load and also to enable the vehicle to accelerate. The road load in terms of rolling, air, grade and curve resistance ar. given below.

The force due to rolling resistance is

$$FRR = (RR + RRC \times AV) \times GCW \qquad (3.3)$$

where FRR = rolling resistance in Kg.

RR = rolling resistance coefficient independent of speed.

RRC = rolling resistance coefficient dependent on speed.

GCW = gross combination weight of vehicle in Kg.

The air resistance is determined at the average velocity using the drag coefficient, frontal exposed area (FA) and atmospheric temperature.

$$FAIR = \frac{P \times C \times FA \times (AV)^2}{(520 + TEMP)} \qquad (3.4)$$

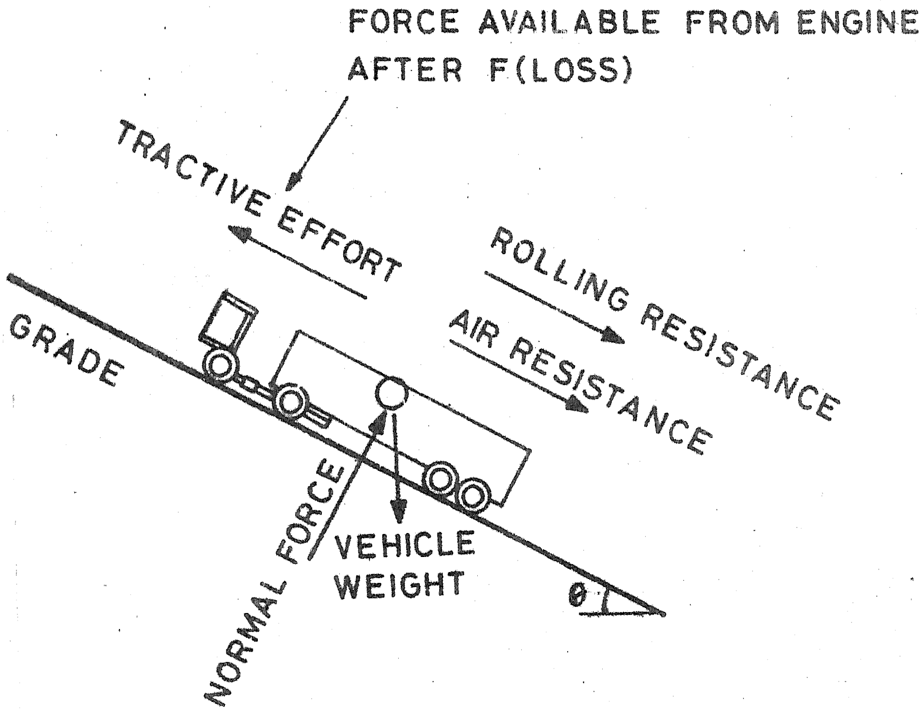


FIG. 8 VEHICLE FREE BODY DIAGRAM

Where FAIR = air resistance in Kg.

FA = frontal area of vehicle in m^2

TEMP = temperature of atmosphere in ^{o}C.

P = constant.

We have assumed the wind velocity over the route to be zero and a standard temperature of $30^{o}C$ in the calculations.

The grade resistance can be obtained from the following equation

$$FG = GCW \times \sin\theta \qquad (3.5)$$

For small values of θ we can approximate $\sin\theta = \theta$. The force tangential to the roadway due to grade will act against the movement of the vehicle if the grade is positive and will add to tractive effort if the grade is negative.

The force due to cornering resistance of the vehicle negotiating a curve is a function of the radius of the curve, speed of the vehicle, weight of the vehicle, number of wheels and average cornering stiffness.

$$FC = \frac{H \times (GCW \times AV \times RCURVE)^2}{WH \times CORNST} \qquad (3.6)$$

Where FC = cornering resistance in Kg.

RCURVE = radius of curvature (=1/Radius) in m^{-1}

WH = number of wheels

CORNST = average cornering stiffness in Kg/Radian

H = constant

When a vehicle accelerates an additional mass will have to be added to the vehicle mass. This mass can be obtained from the following equation

$$FK = FOIC + FOICO\,[RED(N)]^2 \qquad (3.7)$$

Where FOIC and FOICO are vehicle specific constants.

The tractive effort has been used not only to overcome the resistive forces but also it is used to accelerate the vehicle and sometimes we call this as the acceleration resistance. This acceleration ability is obtained from the force equation after deducting the road loads.

$$TE-FRR-FAIR-FG-FC = (GCW/g + FK)\ ACCEL \tag{3.8}$$

where g = acceleration due to gravity (= 9.81 m/sec^2)

ACCEL = average acceleration over the the increment in m/sec^2 which can be expressed as

$$ACCEL = \frac{VF - VI}{TD \times 3.6} \tag{3.9}$$

where VF = final speed after the increment in Kmph

VI = initial speed before the increment in Kmph

TD = time taken over the speed increment in seconds.

After having calculated the average acceleration over the increment it is now possible to obtain the time taken to reach the speed increment by Equation (3.9) and the corresponding distance moved by Equation (3.10).

$$DIST = \frac{AV \times TD}{3.6} \tag{3.10}$$

where DIST denotes the distance moved in metres.

Referring to the engine map specific fuel consumption can be obtained which depends upon the engine rpm and horse power delivered. Fuel consumption over the

speed increment is

$$FUEL = \frac{SFC \times HP \times TD}{3600} \quad (3.11)$$

Where FUEL = fuel consumption over the increment in litres

SFC = specific fuel consumption in litres/hr-hp.

HP = horse power delivered at the engine.

Gradeability can also be calculated which is another way of expressing acceleration ability and is given by

$$GRADEABILITY = \frac{(TE-FRR-FAIR-FG-FC)}{GCW} \times 100 \quad (3.12)$$

3.5 Deceleration Submodel:

When a vehicle travels at a higher speed than the permissible speed then the driver decelerates the vehicle. Deceleration of the vehicle is encountered when a vehicle moves from a level tangent section to an upgrade due to grade resistance or in climbing down the hill. The driver decelerates the vehicle with the help of the

throttle and also by braking. The salient steps of the submodel are given in the following paragraphs. The procedure is essentially the inverse of the acceleration procedure which is shown in Figure 9.

We first calculate the tractive effort required to match the rate of deceleration of the vehicle under the given road load conditions. During deceleration a speed decrement of ΔV is used in order to compute the state variables of the vehicle. The deceleration of the vehicle is substituted for ACCEL in Equation (3.8) and the corresponding tractive effort is calculated. We now proceed to determine the corresponding horse power required at the engine. If the power required is less than certain minimum power then we use a prespecified minimum power for computation of fuel consumption.

3.6 Steady State Submodel:

When a driver attains his desired speed over the given stretch of highway he attempts to maintain this uniform speed till interaction becomes significant due to traffic and geometry. We calculate the road load due to

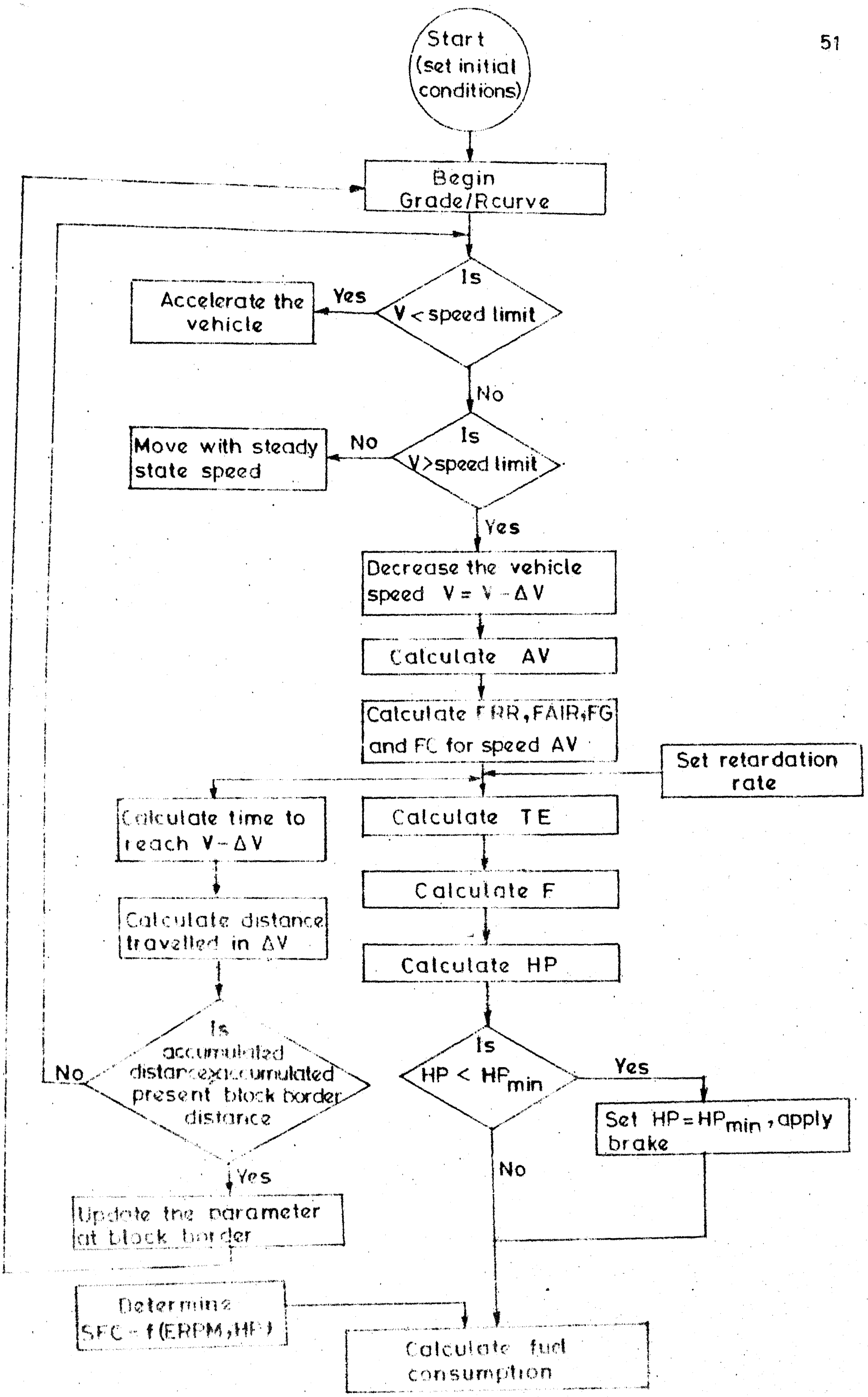


FIG. 9 DECELERATION SUBMODEL

rolling, air, grade and curve resistances and compute the tractive effort required to overcome these forces for the given vehicle speed. The calculation of tractive effort is made through Equation (3.8) by substituting the value of ACCEL to be zero. The fuel consumption calculation proceeds in the similar manner to that of deceleration submodel and shown in Figure 10.

3.7 Gearshift Submodel:

Gear changes are normally performed by drivers by either upshifting or downshifting from one gear to the other. A vehicle can be operated in a given speed range bounded by upper gearshift speed and lower gear shift speed. For example Ashok Leyland vehicle can be operated in the first gear upto the speed of 10 Kmph and in the second gear upto 16 Kmph.

Gearshift is made when the vehicle reaches a pre-specified speed by the manufacturers called the gearshift speed, Also, gearshift is made when the vehicle reaches the speed corresponding to the maximum horse power. An upward gear change is made when the vehicle accelerates

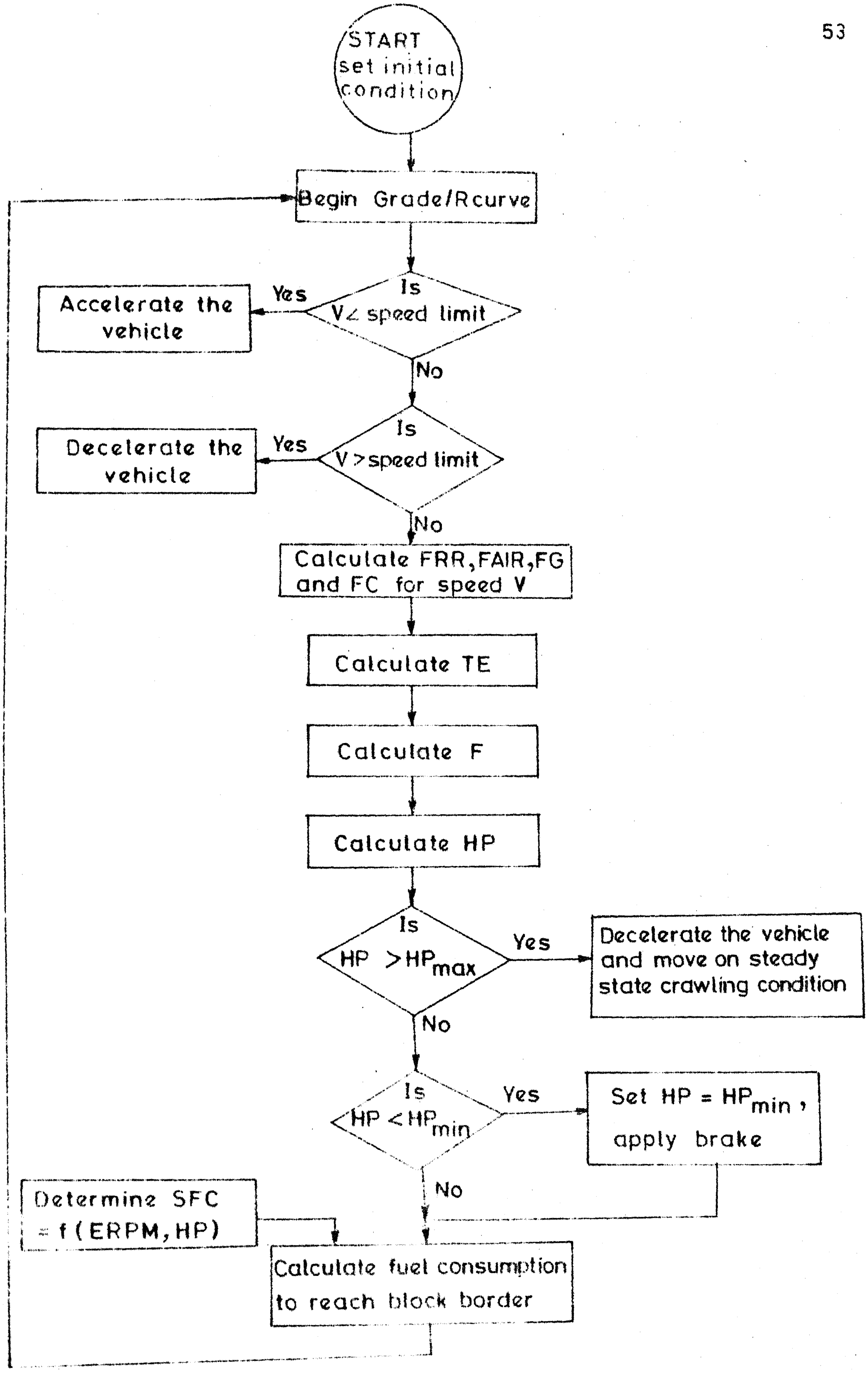
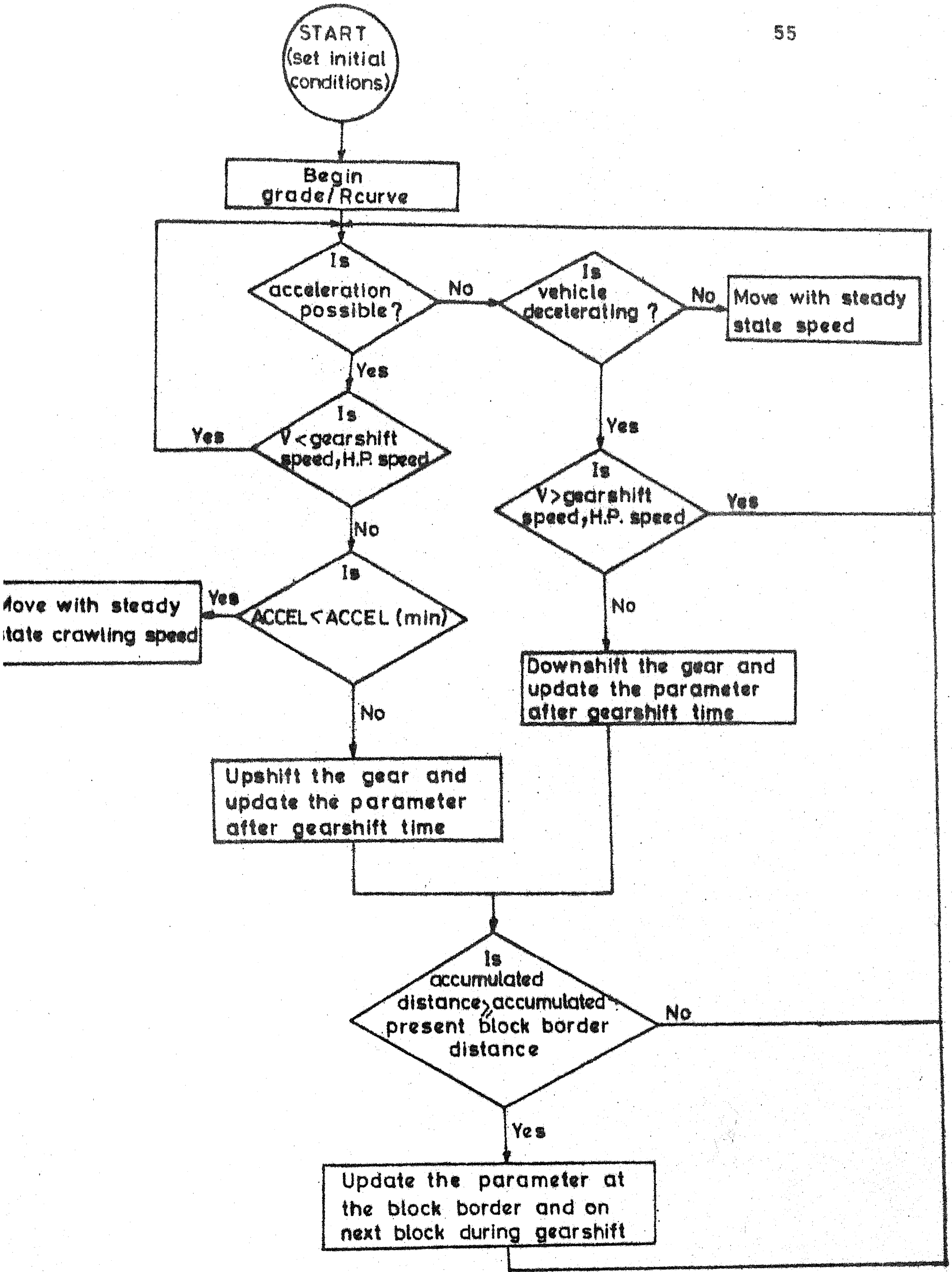


FIG. 10 STEADY STATE SUBMODEL

and reaches the upper gearshift speed. Similarly the gear is changed to a lower gear if the vehicle decelerates and reaches the lower gear shift speed. The gearshift process involves some time duration which will vary with the drivers. During the gearshift the drive train mechanism is disengaged from the crankshaft and the vehicle nowcoasts due to its momentum and a certain loss of speed will result. By using the force Equation (3.8) the speed of the vehicle at the end of the gearshift is determined and the rate of change of speed during the gearshift time is calculated. The corresponding engine rpm can be obtained from Equation (3.1) when the average speed is calculated from the initial speed before the gearshift and the final speed after the gearshift and substituted for AV. Similarly the distance covered during the gearshift time can be calculated from the Equation (3.10). During the gearshift it is assumed that no fuel is consumed since the engine is essentially operating with empty strokes due to momentum of crankshaft. The flow logic has been shown in Figure 11.



FIG·11 GEAR SHIFT SUBMODEL

3.8 Driver Perception Decision Submodel:

During the transition from one homogeneous road block to another the driver has to perceive the status of his vehicle and take appropriate measures to maintain the corresponding desired speed in the current road block. The vehicle may accelerate or decelerate depending upon the type of transition. The driver requires enough time to perceive the change in the vehicle status in terms of speed. Till he perceives the speed change he normally uses the tractive effort which he has been using in the previous road block at the steady state condition. If during this process the engine reaches the maximum/minimum prespecified speed for a given gear, the gear is shifted. We specify a threshold value for the difference between steady state speed of the previous block and the current speed of the vehicle. In order to arrive at a decision point for the driver to accelerate or decelerate, we increment the state change of vehicle at fixed increment of time interval which has been taken in the model as 1 second. The driver decision time is determined from the specified threshold speed difference and a fixed time duration. We have arbitrarily chosen 5 seconds

as the time duration to reach decision point, in case he fails to attain the threshold speed difference during the specified 5 seconds. The calculation proceeds with 1 second time increment and the flow logic is similar to that of gearshift submodel and shown in Figure 12.

The above sections have briefly described the various aspects of the simulation model. We proceed to simulate the vehicle performance and fuel consumption for typical automative vehicles over a hypothetical 10 Km route the results of which is given in the next chapter.

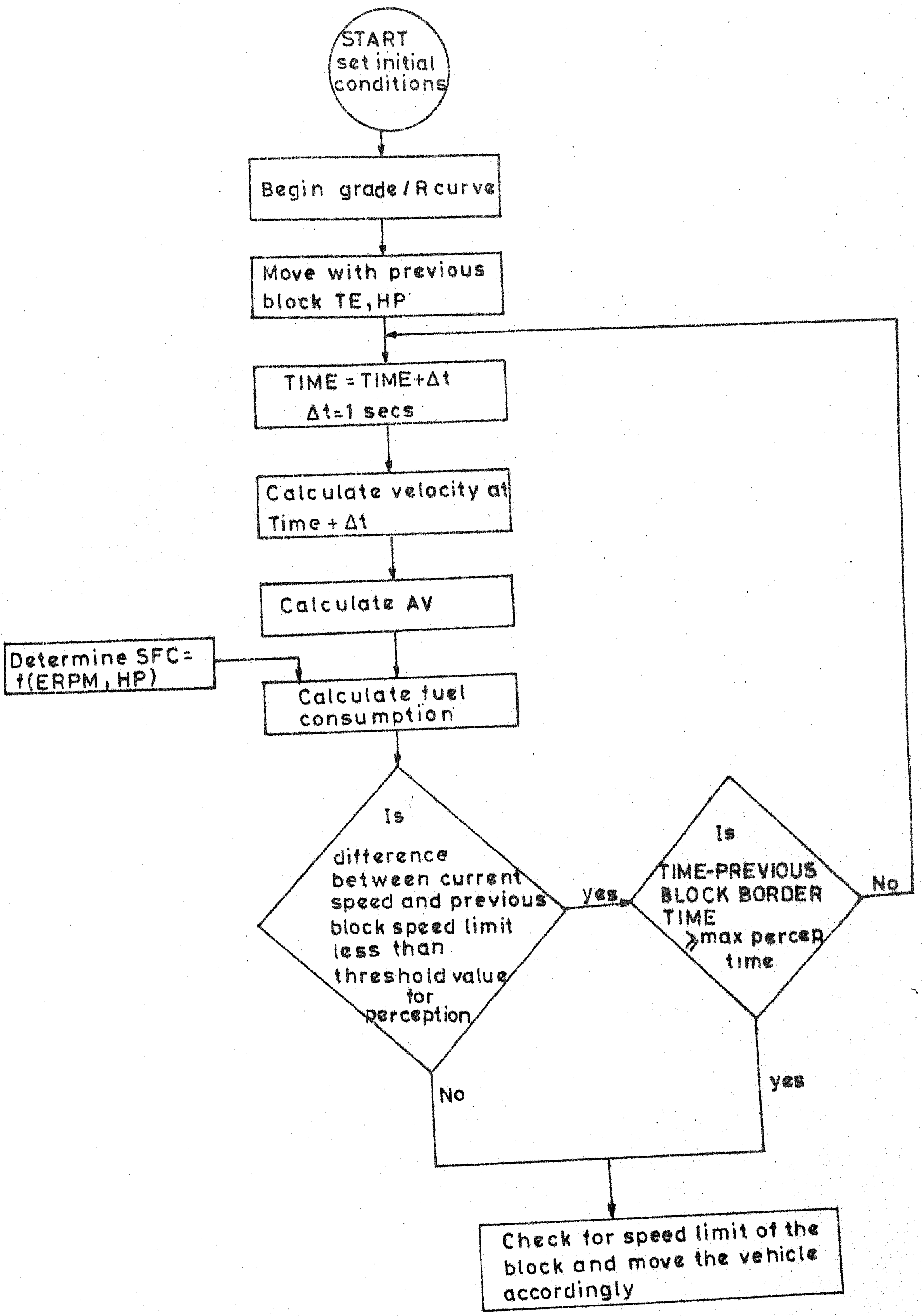


FIG. 12 DRIVER PERCEPTION DECISION SUBMODEL

CHAPTER IV

PREDICTION OF VEHICLE PERFORMANCE AND FUEL CONSUMPTION FOR TYPICAL ROAD VEHICLES

The detailed flow logic for simulation model has been developed and given in the previous chapter for various components of traffic systems. We have simulated the performance of three types of Ashok Leyland models and the Ambassador car for which we could get required data concerning their performance. These vehicles have been analysed for the steady state movement as well as free flow conditions on a 10 Kilometre hypothetical roadway consisting of 13 homogeneous roadway sections. The following sections give the vehicle and route data used in the calculation.

4.1 Vehicle and Roadway Data:

The data pertaining to vehicles used in the model (See Table 2) have been taken from the published handbooks of respective manufacturers.

The vehicles have been simulated over a hypothetical 10 Kilometre route. The homogeneous blocks

TABLE 2

ROUTE DATA

Block Number	Length (m)	Gradient	Curve Radius (m)	Speed Limit (Kmph)
1	300	0.0125	0.0	55
2	810	-0.0100	0.0	55
3	400	0.0060	0.0	55
4	390	-0.0056	0.0	55
5	600	0.0200	0.0	50
6	600	-0.0150	0.0	55
7	1000	0.0350	0.0	40
8	1000	-0.0100	0.0	55
9	700	0.0120	0.0	55
10	500	-0.0150	300.0	30
11	800	0.0200	0.0	50
12	2000	-0.0200	0.0	50
13	1000	0.0000	0.0	60

TABLE 3

VEHICLE DATA

Specifications	Vehicle Type			
	Ashok Leyland Passenger Viking	Ashok Leyland Titan Passenger Double Decker	Ashok Leyland Comet Haulage	Hindustan Motors Ambassador Car
1	2	3	4	5
Unladen weight (kg)	3780	4420	3740	1116
Fully Laden Weight (kg)	10780	12985	12196	1528
Engine type	AL 370 power plus 6 cylinder, 110 bhp at 2400rpm			4 cylinder ohv, 46 bhp at 4250rpm
Gear ratios	(5 speeds) Ratio Gear number 6.988:1 I 4.216:1 II 2.655:1 III 1.605:1 IV 1.:1 V 0.76:1 VI(optional) 6.343:1 Reverse	Same as passenger viking	Same as passenger viking	(4 speeds) Ratio Gear number 3.8069:1 I 2.2529:1 II 1.5060:1 III 1.1 IV 3.8069:1 Reverse

Contd....

Table 3 contd...

1	2	3	4	5
Rear axle gear type and ratio	Single spiral bevel gear 5.833:1	Same as passenger viking	Same as passenger viking	Single bevel gear 4.875:1
Number of wheels	6			4
Frontal area	7.0 (assumed)	11.0(assumed)		2.4 (assumed)
Drag coefficient	0.75(assumed)	Same as passenger viking	Same as passenger viking	0.65(assumed)
HP_{min}	22.5 (assumed)			7.00(assumed)
FOIC	45.0 (assumed)			10.00(assumed)
FOICO	0.5 (assumed)			0.25(assumed)

Rate of deceleration	2 m/sec^2
Gearshift time	2 secs
Max.Perception time	5 secs
Threshold value of speed	3 Kmph
H (Constant)	0.1
P (Constant)	2.50
CORNST	9740 kg/radian
Density of Diesel(assumed)	0.80

4.2 Interpretation of Results:

The space time trajectories of the simulated vehicles over a level tangent roadway are shown in Figure (13a). The relationship between speed and time under full throttle condition on a level roadway section are given in Figure (13b) for the fully loaded vehicles namely Ashok Leyland Comet model, passenger model, double decker model and Ambassador Car. The figures clearly indicate the differing performance characteristics of the various vehicles. As expected the performance curves indicate the decreasing acceleration capability as the speed increases and this variation is nonlinear. The

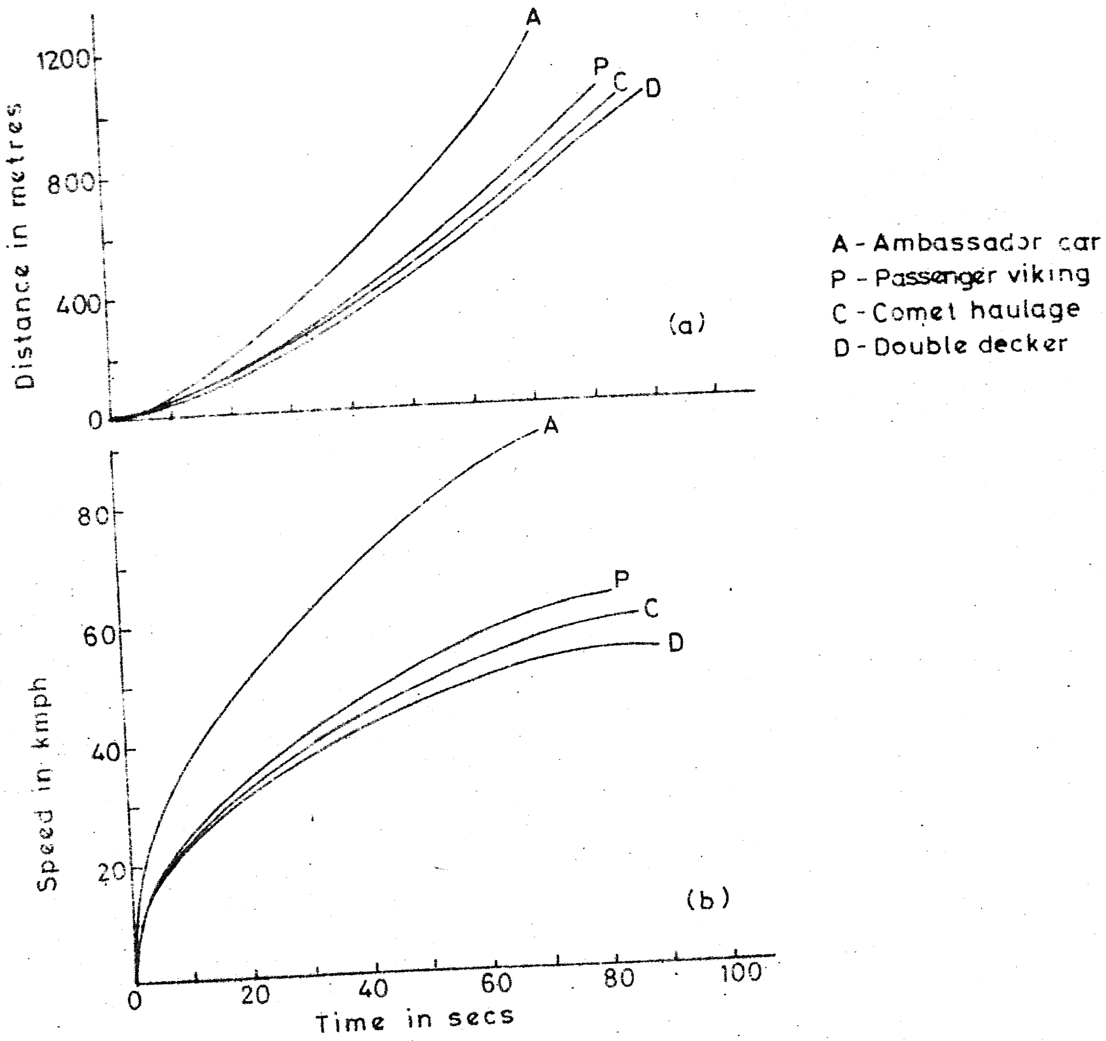


FIG. 13 VEHICLE PERFORMANCE CURVES

values obtained from performance curves could be used in the simulation of traffic during overtaking and crossing manouevres when interaction becomes significant.

The tractive effort available at wheels as a function of the speed in the case of acceleration of a vehicle is shown in Figure 14 for the Comet model. The vehicle will have zero acceleration when the tractive effort at the given speed equals the road resistances. The non-linearity observed in reduction of acceleration ability found in the Figure 13b is due to reduction in the available tractive effort in higher gears when the speed increases. This functional form of the tractive effort vs speed imparts the required credibility to the simulation model in which the vehicle performance has been taken into account.

Gradeability has been defined earlier as the ratio of the net force available at the wheels to the gross combination weight of the vehicle. As the speed of the vehicle increases, gradeability decreases and this is exhibited by the Figures 15 and 16. Also shown in the Figures 15 and 16 the time to accelerate from the rest. The upshift of the gears and its effect on the time to

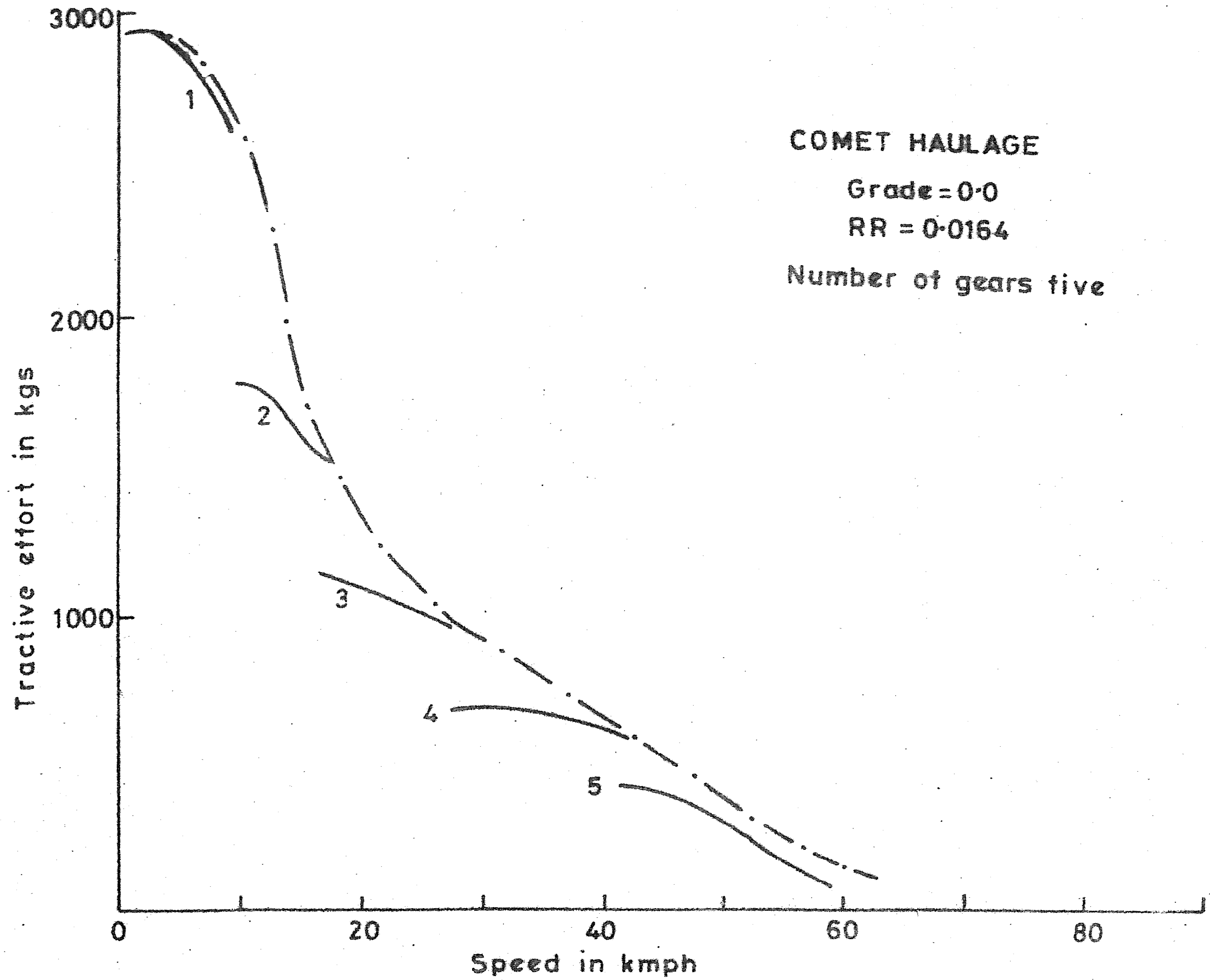
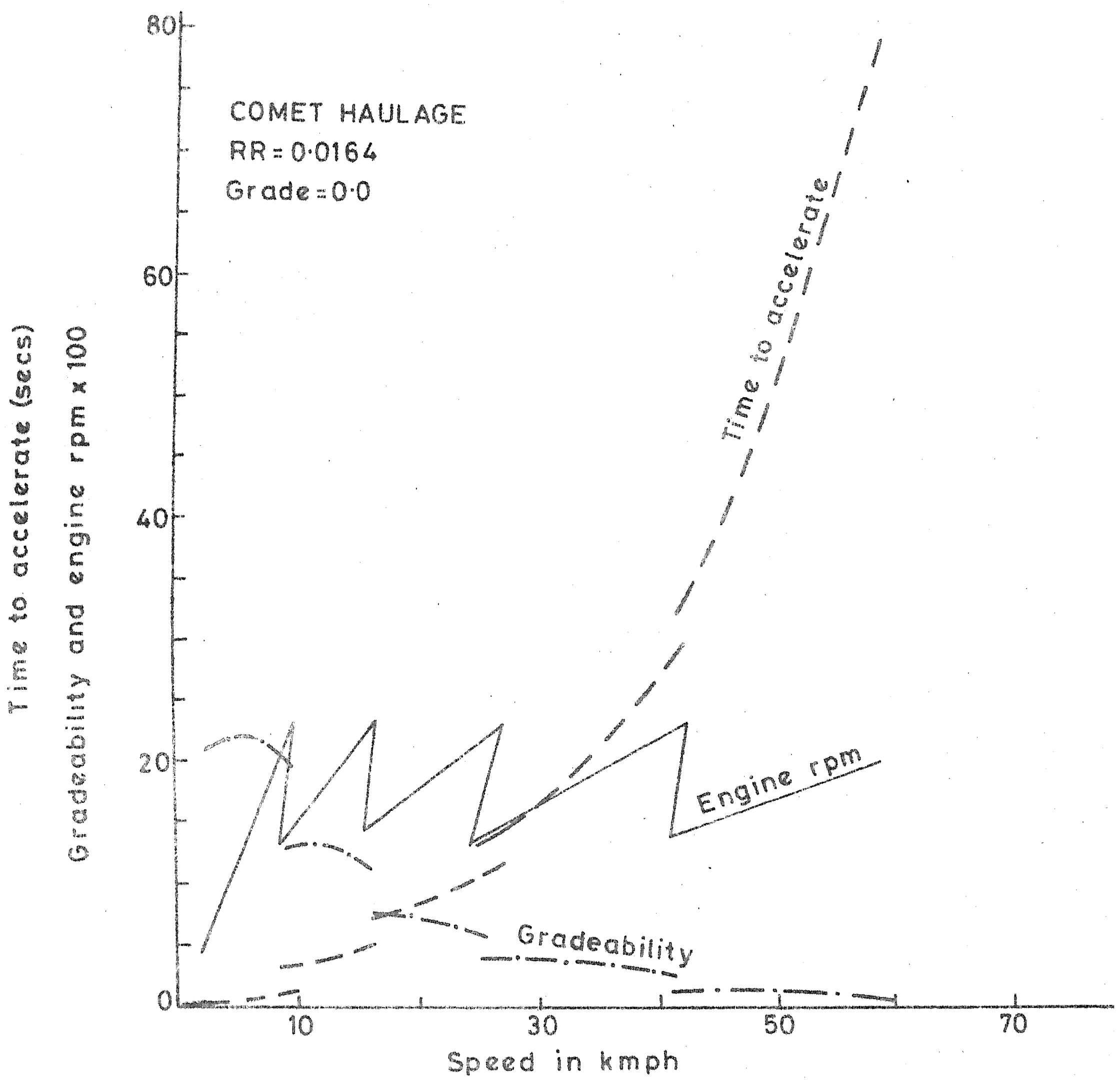


FIG. 14 TRACTIVE EFFORT VS SPEED



FIG·15 VEHICLE PERFORMANCE AT VARIOUS TRANSMISSION RATIOS

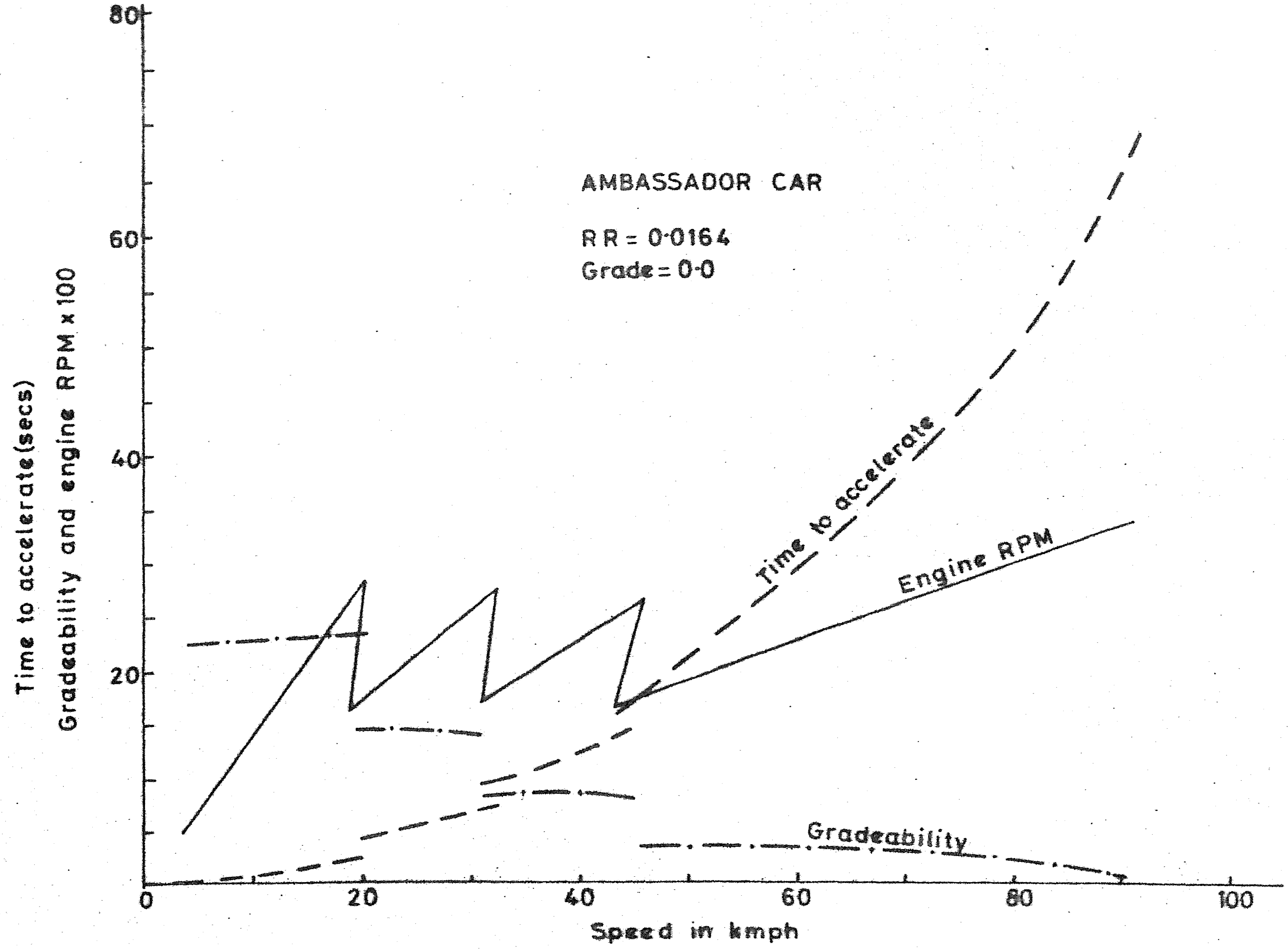


FIG.16 VEHICLE PERFORMANCE AT VARIOUS TRANSMISSION RATIOS

accelerate are also shown. The linear variation of the engine rpm at various gears can be observed from these figures. The engine speed is low at the initial start conditions upto 2 Kmph for the Comet model. The engine rpm is increased till the gearshift speed is reached (see Figure 15).

The fuel consumption in litres/100 Km at steady state speeds on a level tangent section and for various pay load conditions are shown in Figure 17. For example empty Comet vehicle consumes approximately 10 litres of fuel per 100 Kilometres which corresponds to an operating speed of about 45 Kmph. (The actual fuel consumption will be little higher than what is obtained by simulation. This discrepency is due to two factors. 1) We have assumed an ideal road having rolling resistance corresponding to high type pavement. The fuel consumption increases with increase in roughness but also this varies nonlinearly with the speed. 2) We have used the data supplied by manufacturer in which the specific fuel consumption has been assumed to be constant irrespective of the horse power. Therefore the values for the fuel consumption shown in the figure are smaller than what will be expected when above factors are taken into account.

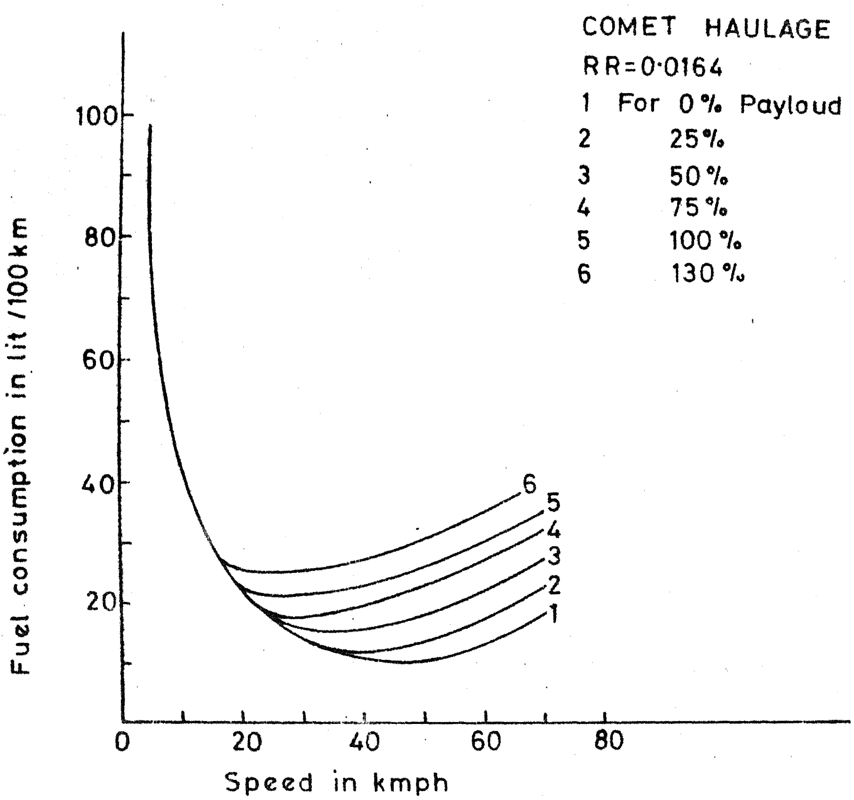


FIG.17 FUEL CONSUMPTION VS SPEED

However the simulation model is able to replicate the the fuel consumption fairly well for the given data. As the pay load increases the fuel consumption increases at a lesser rate and the optimal speed corresponding to the lowest fuel consumption rate shifts towards lower speeds.

The variation of fuel consumption has been obtained for varying the rolling resistances and shown in Fig. 18a. As the rolling resistance is increased the fuel consumption increases and the optimal speed corresponding for lowest fuel consumption decreases.

Figure 18b shows the fuel consumption at various speeds for three models of Ashok Leyland. The fuel consumption rate is higher for double decker than the other two models because of increased mass and frontal area. Comet haulage has the same area but more mass than passenger model and hence the rate of fuel consumption is higher.

The fuel consumption vs speed curves are given for grades varying from 0 to 5 percent for the Comet model (see Figure 19). The fuel consumption increases with

COMET HAULAGE FULL LOADED

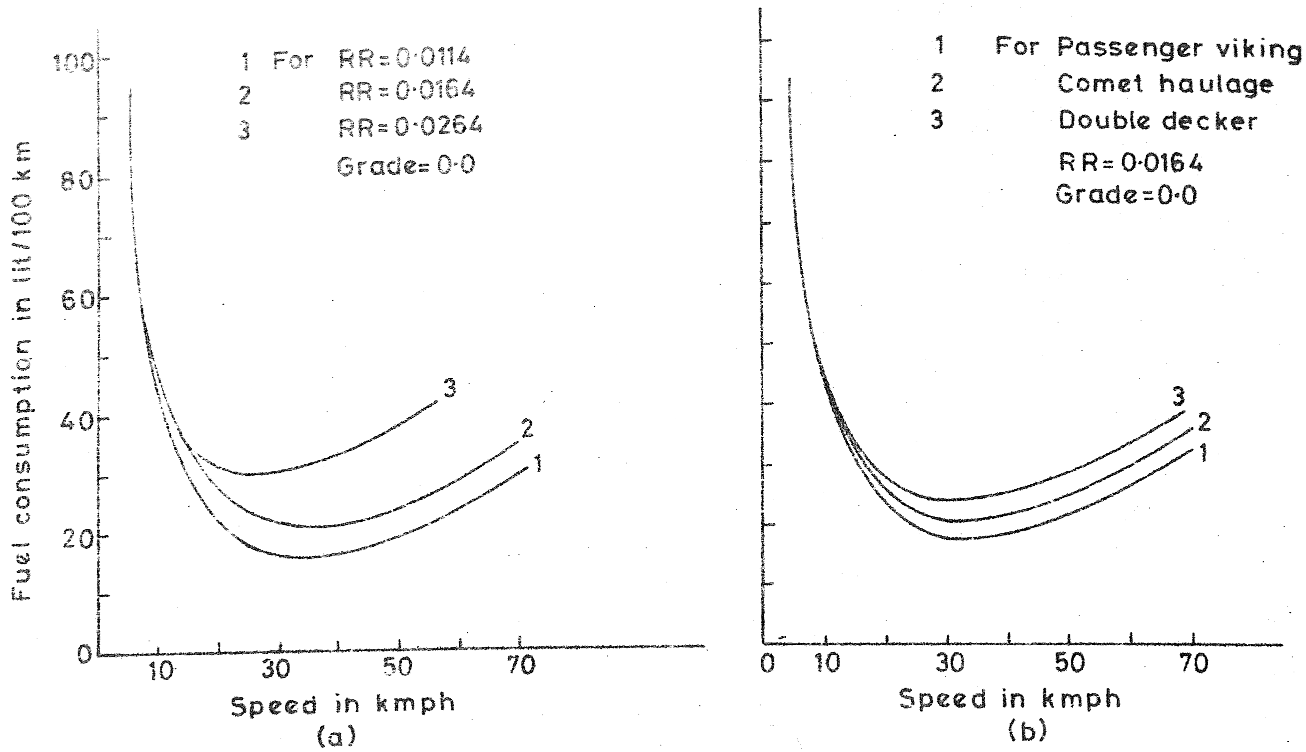


FIG.18 FUEL CONSUMPTION VS SPEED (Constant speed)

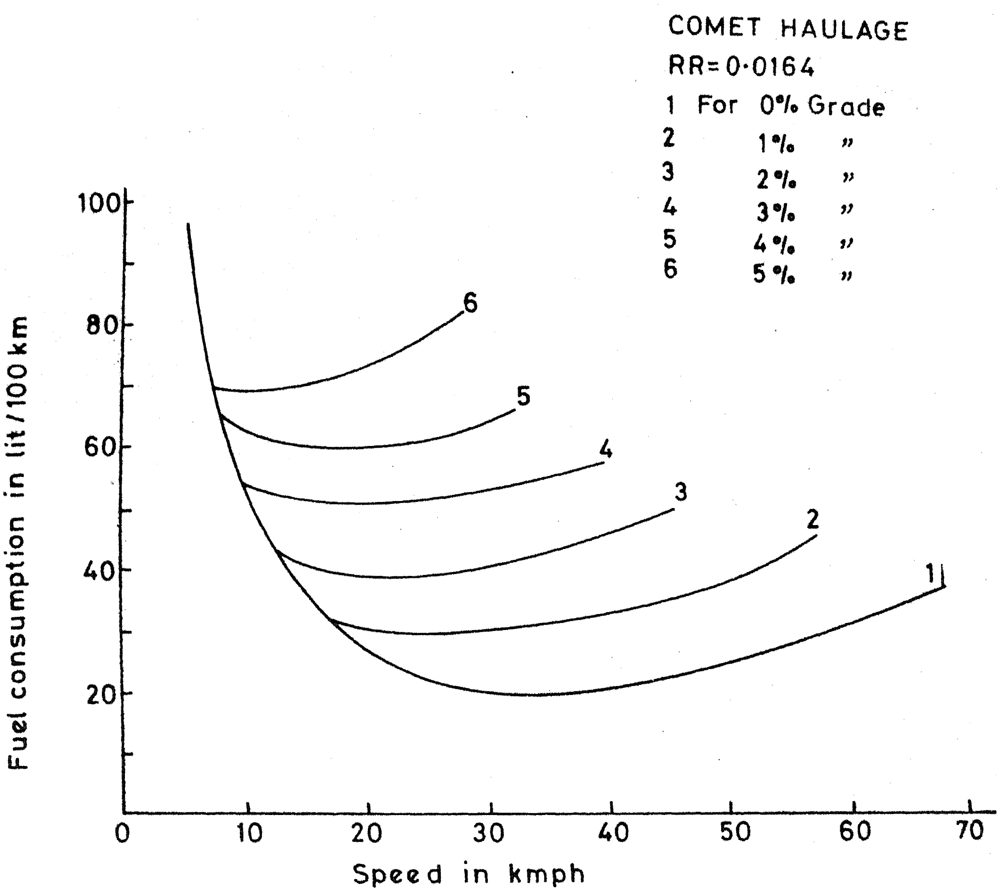


FIG.19 FUEL CONSUMPTION VS SPEED (Constant speed)

increasing grade which is similar to variation exhibited for rolling resistance coefficient.

Figures 20 and 21 show the steady state fuel consumption calculations for Ambassador Car for various rolling resistance coefficients and grades. The relationships are very similar to the Ashok Leyland vehicles. However, it can be noted that beyond the optimum speed the rate of increase in fuel consumption with speed is less compared to trucks simulated. This is due to the fact that the streamlining of the Ambassador Car has reduced the air resistance considerably compared to trucks.

The simulated road stretch is 10 Km. long consisting of 13 homogeneous blocks. The vertical profile of the route is given in Figure 22 b. A horizontal curvature of radius 300 m has been introduced in block number 10 from 5700 m to 6200 m with appropriate transition curves. The roadway is assumed to posses a high quality pavement with rolling resistance coefficient 0.0164. Sample calculations of the model are given in Appendix.

Figure 23 shows the velocity profile for the Ashok Leyland Comet truck fully loaded and for the

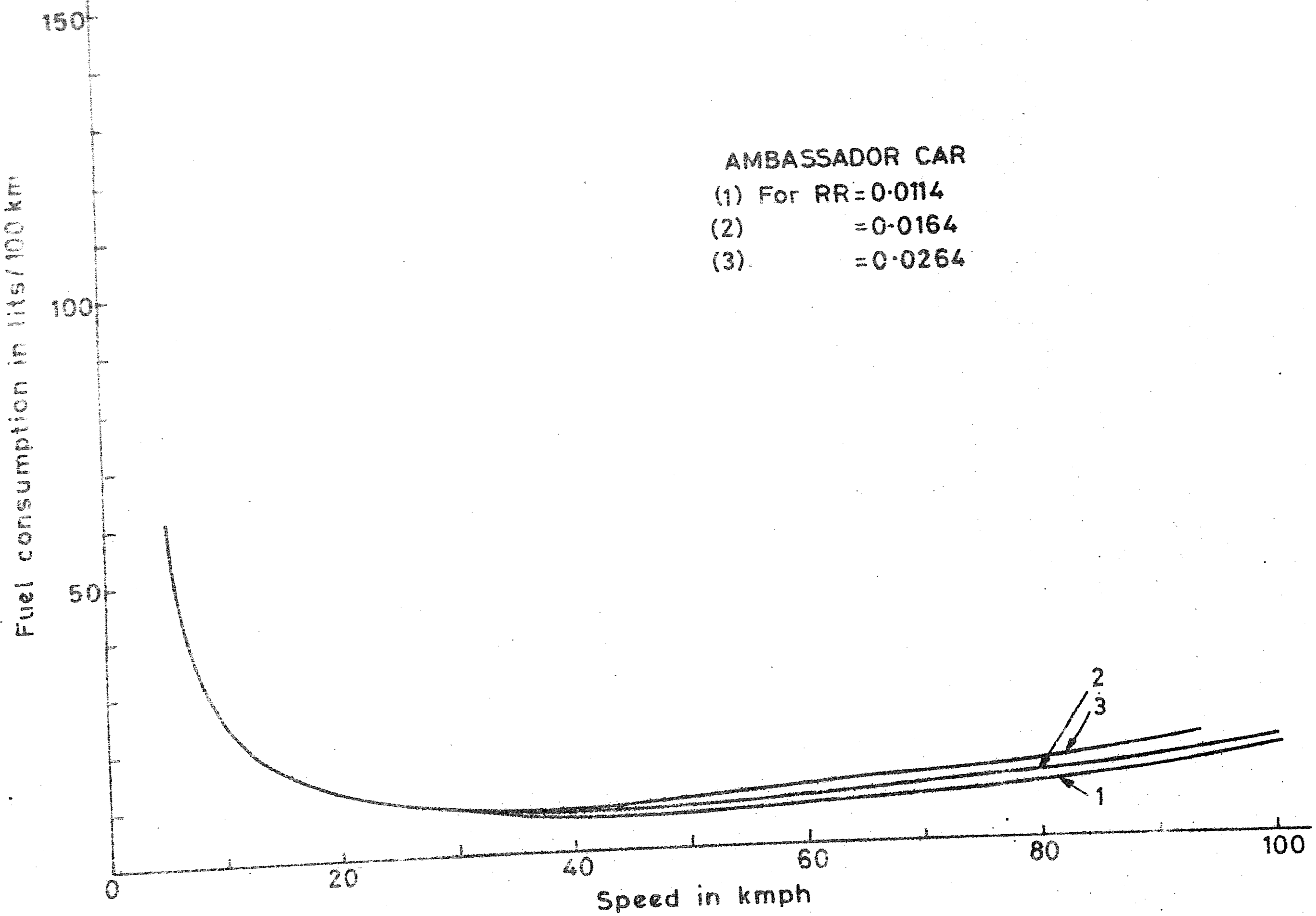


FIG.20 FUEL CONSUMPTION VS SPEED (Constant speed)

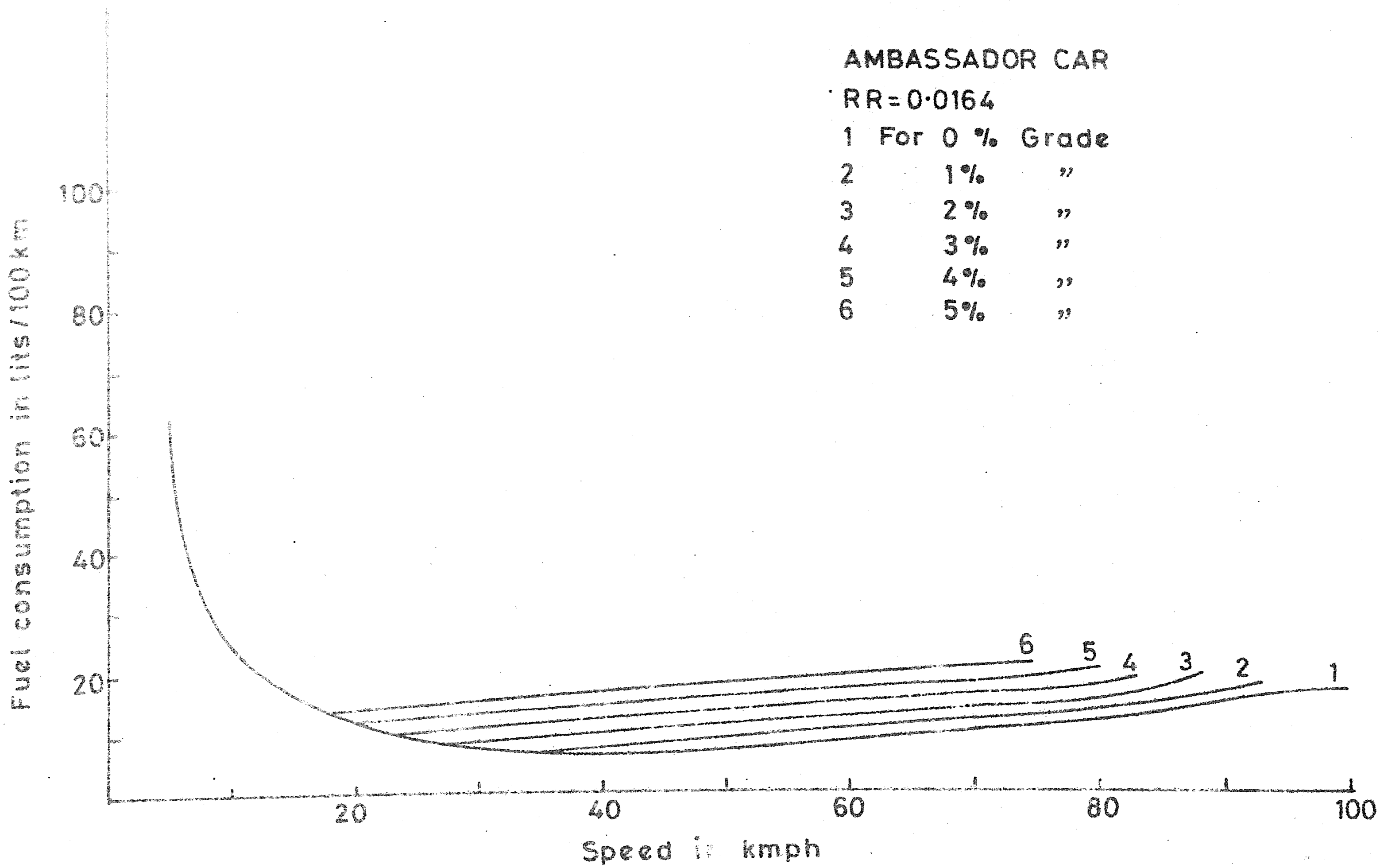


FIG. 21 FUEL CONSUMPTION VS SPEED (Constant speed)

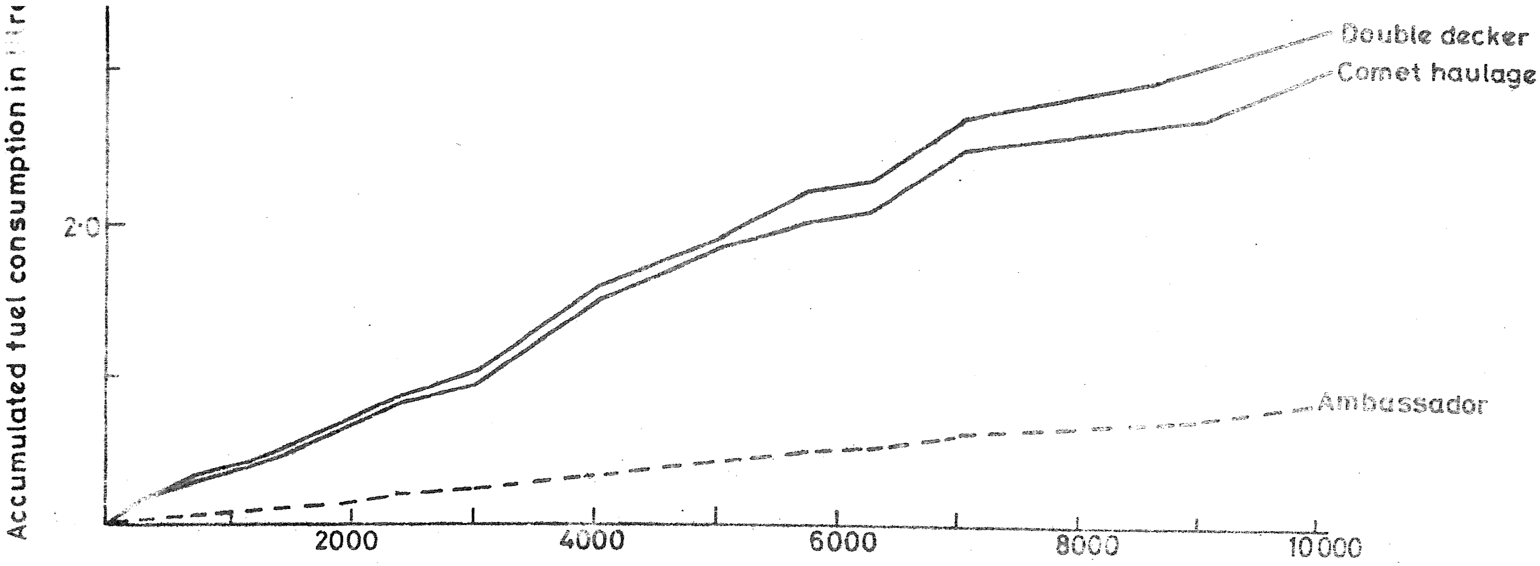


FIG. 22 a ACCUMULATED FUEL CONSUMPTION VS DISTANCE

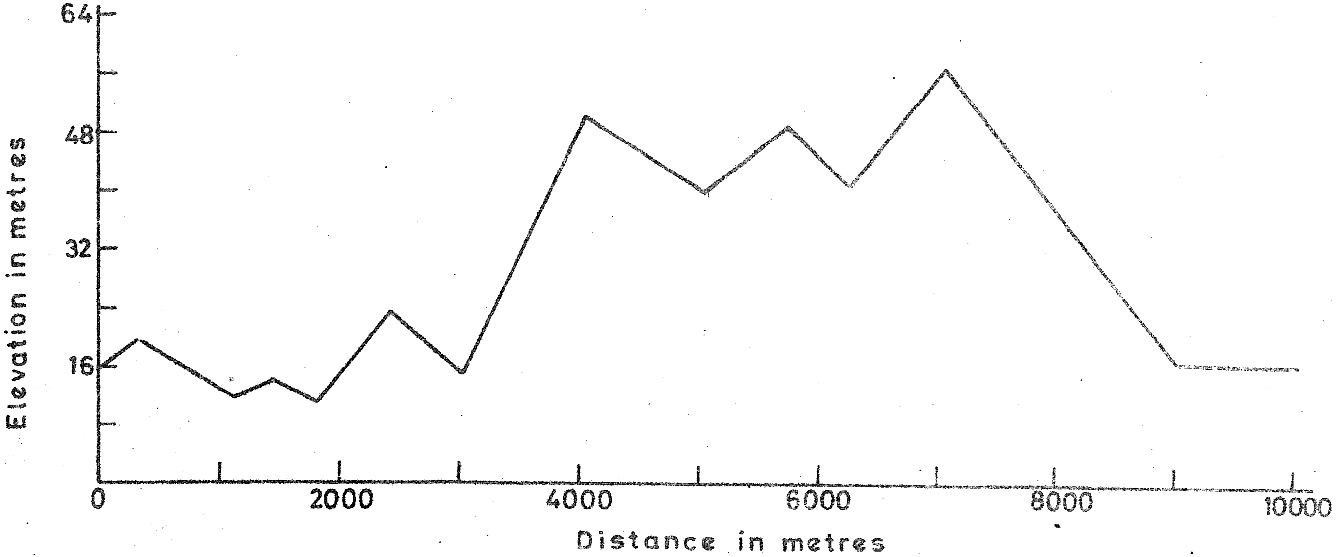


FIG. 22 b VERTICAL PROFILE OF THE SIMULATED ROAD

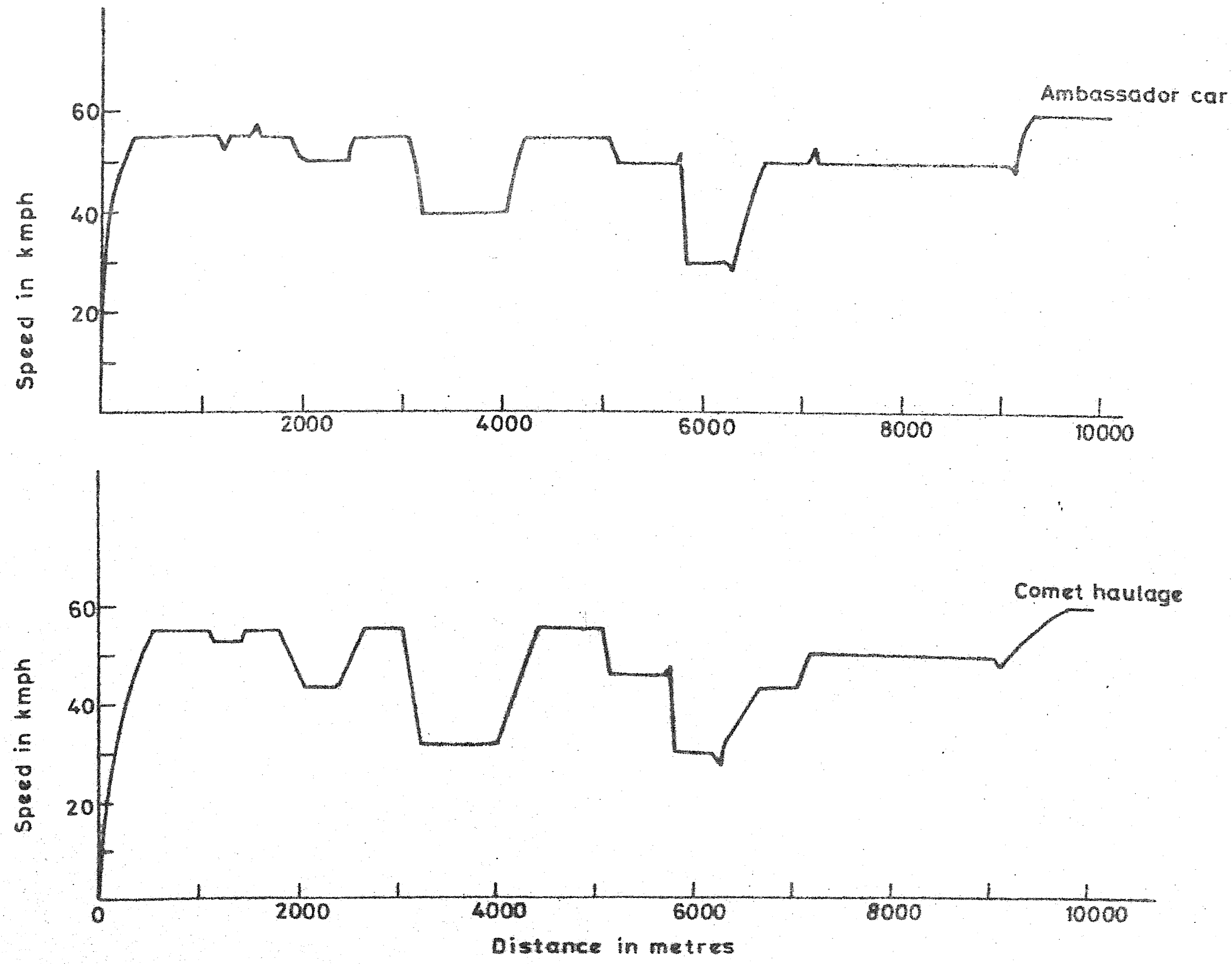


FIG. 23 VELOCITY PROFILE

Ambassador Car. It can be seen from the Figure 23 that the velocity profiles attempt to represent the expected behaviour on the simulated route. The fully loaded comet truck is unable to reach the specified speed limit on XIth block. While the Ambassador Car could negotiate the route to the posted speed limit. This shows that the performance capability of these two types of vehicles are adequately represented in the simulation model along with the driver behaviour and the driver perception decision time and the corresponding vehicle trajectories during this time can be found in the respective profiles wherever there is a transition from one block to another. Also it can be observed from the speed profile of the truck in block IIIrd, Vth, VIIth and Xth that it has decelerated from higher speed and was unable to move with the speed limit posted for that section and travelled at steady state crawling condition. The acceleration performance of these two types of vehicle can be seen from space time trajectories during acceleration.

The cumulative fuel consumption for the simulated movement of Ashok Leyland double decker model, Comet model

and also the Ambassador Car are shown in the Figure 22a. The cumulative values represents the fuel consumed which is a function of roadway geometry, speed and acceleration/deceleration. For this stretch the Ashok Leyland comet consumes approximately 3 litres of diesel and Ambassador Car 0.85 litres which are quite rational as compared to the average figures supplied by the manufacturer (Comet haulage consumes 20-22 litres for 100 Km)

The transport productivity (Net ton - Km/litre) vs. pay load is given in Figure 24. As the pay load increases the transport productivity increases at the decreasing rate. This would also explain why truckers prefer to overload in maximizing their immediate returns in terms of productivity.

Data concerning fuel consumption for the steady condition and for the free flow condition are not available and hence the simulation model outputs have not been compared to the actual conditions obtaining in the real world. However it can be seen that the model tries to represent the performance and fuel consumption rather well in qualitative sense and therefore the model can be accepted.

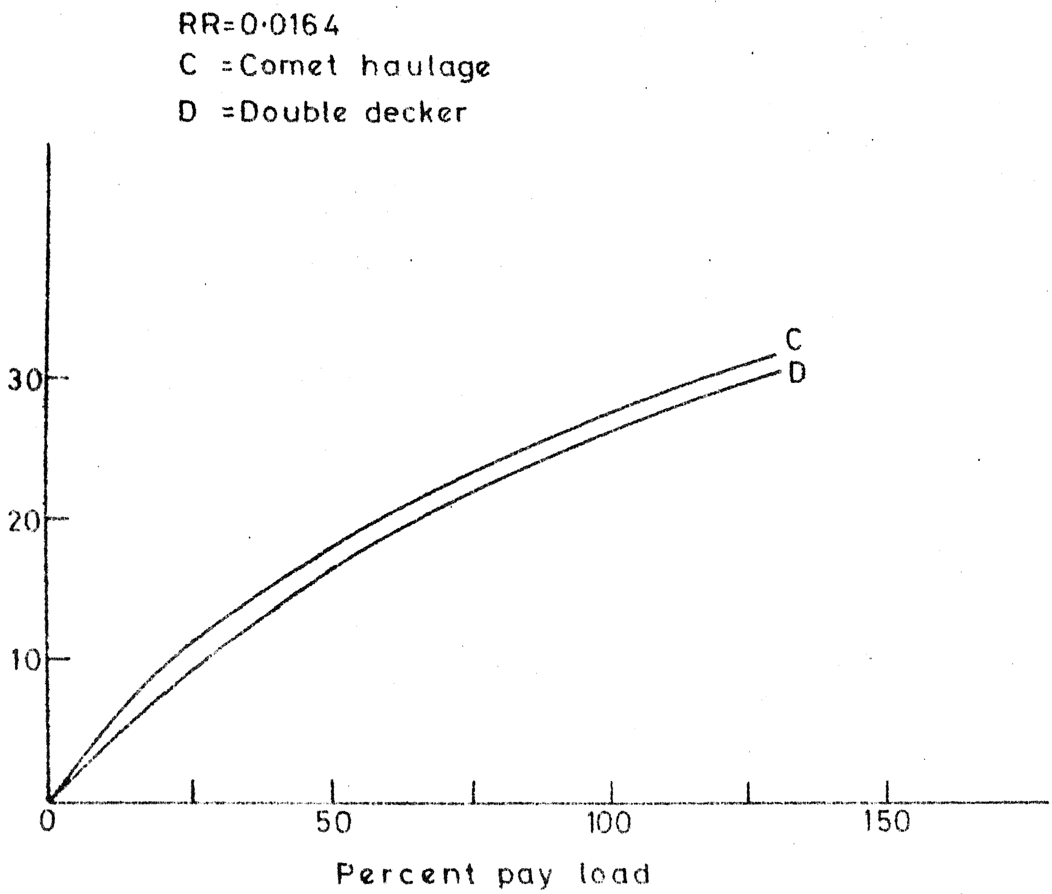


FIG.24 TRANSPORT PRODUCTIVITY VS PERCENT PAYLOAD

4.4 Conclusions and Suggestions for Further Study:

(1) In this study we focussed our attention in understanding the interaction of factors affecting the fuel consumption of free moving roadway vehicles. We consider this study as the most crucial step in estimating the fuel consumption for any traffic condition. We have not considered the interaction amongst the vehicles which would significantly affect the free movement and therefore energy consumption. The submodels can be gainfully deployed in a traffic model in which interaction is taken into account. This would call for minor modifications which could be readily incorporated.

(2) A limited type of vehicles have been used on a hypothetical roadway in analysing the performance characteristics and fuel consumption. We could not validate the outputs of the simulation model by collecting realworld data due to nonavailability of an instrumented vehicle. Validation part of the proposed model can be studied with the help of the data which will be available in the future from Road User Cost Study project currently

under progress at the Central Road Research Institute, Delhi.

(3) In the fuel consumption calculations we have assumed the driver uses the maximum power available at the engine during acceleration mode. This is unrealistic as we find that drivers normally use only a fraction of maximum power available at the engine in driving. Data can be collected at various speeds for various drivers and a relationship can be developed between the used power and maximum available power at the engine. It is essentially the difference between what the engine is capable of delivering and what the driver is willing to use. This correction can be incorporated in the computation of fuel consumption which sould result in accurate prediction.

(4) In this study we have not considered the roughness of the roadway pavement which has a marked effect on fuel consumption especially at higher speeds of operation. A relationship representing the road roughness and fuel consumption can be developed and can be incorporated in the model. Alternatively it is possible to consider the road

roughness in the force equation by suitable modification of rolling resistance coefficients. Essentially this would involve a correlation analysis between the road-roughness and rolling resistance coefficient.

(5) In the calculation of fuel consumption we have used the diagram supplied by the manufacturers which do not contain the data regarding the variation of specific fuel consumption as a function of horse power developed. Currently available values represents specific fuel consumption as a function of engine rpm only at full throttle conditions. This would distort the fuel consumption estimates. Therefore an attempt can be made to obtain the complete engine map and incorporate the required modification in the model.

(6) Further research can be directed towards correlating the acceleration noise with the fuel consumption for free flow as well as interaction traffic. We did not make explicit calculations of acceleration noise in this study due to paucity of data for validation. However we have simulated vehicle movement for a small speed increment and assumed the roadway to exhibit noise due to

speed changes in the transitions zones between homogeneous blocks.

(7) We do not claim the logic proposed in the submodel is perfect. The submodels can be improved further to impart realism to the desired extent in arriving at the fuel consumption estimates.

REFERENCES

1. Gerlough, D.L. and Capelle, D.G., An Introduction to Traffic Flow Theory, Special Report 79, Highway Research Board, U.S.A., 1964.

2. Gynnerstedt, G., 'Fuel Consumption Notes', Personnel Communication, 1981.

3. Gravem, S., 'Fuel Consumption Model' a Mimeograph, Oslo, 1979.

4. Gyenes, L., 'Fuel Utilization of Articulated Vehicles: Effects of Powertrain Choice', Department of Environment Department of Transport, TRRL Report SR 586, Crowthorne, 1980.

5. Leilich, R.H., Cohen, R.D., Green, A., and Kendrick, M.J., 'Energy and Economic Impacts of Projected Freight Transportation Improvement', U.S. Department of Transportation, Washington, D.C., 1977.

6. Moon, W.D., 'Computer Simulated Vehicle Performance', Society of Automotive Engineers, Newyork, 1962.

7. Renouf, M.A., 'An Analysis of Fuel Consumption of Commercial Vehicles by Computer Simulation', Department of Environment Department of Transport, TRRL Report 973, Crowthorne, 1980.

8. Report of the Working Group on Energy Policy , Planning Commission, New Delhi, 1979.

9. William, T., 'Energy Losses in Heavy Commercial Vehicles', Department of Environment Department of Transport, TRRL Report SR 329, Crowthrone, 1977.

10. William, T., 'Power Consumption of Tyres', Department of Environment, TRRL Report SR 192, Crowthorne, 1975.

11. Wilson, D.E. and Nowottny, P.M., 'An Instrumented Car to Analyse Energy Consumption on the Road', Department of Environment Department of Transport, TRRL Report LR 787, Crowthrone, 1977.

APPENDIX

COMET HAULAGE FULL LOADED

F(LOSS) = 15%

START GEAR NUMBER = 1

VELOCITY MET/S	GRADE	ERPM RPM	ACCEL MET/S/S	NHP HP	TR-EF KG	TIME S	DIST MET	FUEL LIT
0.50	0.0125	450.000	15.774	22.5	20941.9	0.01	0.00	0.00001
1.00	0.0125	450.000	5.078	22.5	6980.6	0.04	0.01	0.00006
1.50	0.0125	450.000	2.938	22.5	4188.4	0.08	0.02	0.00014
2.00	0.0125	450.000	2.021	22.5	2991.7	0.15	0.06	0.00025
2.50	0.0125	534.988	1.848	26.7	2766.3	0.23	0.10	0.00039
3.00	0.0125	653.874	1.848	32.7	2766.3	0.30	0.16	0.00055
3.50	0.0125	772.761	1.847	38.6	2766.3	0.38	0.23	0.00074
4.00	0.0125	891.647	1.891	45.5	2823.2	0.45	0.30	0.00095
4.50	0.0125	1010.533	1.934	52.6	2880.2	0.52	0.39	0.00118
5.00	0.0125	1129.419	1.958	59.4	2911.9	0.59	0.48	0.00144
5.50	0.0125	1248.306	1.981	66.4	2942.9	0.66	0.59	0.00171
6.00	0.0125	1367.192	2.006	73.5	2975.6	0.73	0.70	0.00201
6.50	0.0125	1486.078	2.008	80.0	2979.1	0.80	0.82	0.00233
7.00	0.0125	1604.965	2.002	86.2	2971.5	0.87	0.95	0.00267
7.50	0.0125	1723.851	1.961	91.0	2919.2	0.94	1.09	0.00304
8.00	0.0125	1842.737	1.921	95.5	2867.2	1.01	1.24	0.00345
8.50	0.0125	1961.623	1.878	99.7	2810.8	1.09	1.41	0.00389
9.00	0.0125	2080.510	1.831	103.4	2750.1	1.16	1.60	0.00436
9.50	0.0125	2199.396	1.785	107.0	2691.2	1.24	1.80	0.00487
10.00	0.0125	2318.282	1.712	108.8	2595.9	1.32	2.02	0.00542

GEAR UPSHIFT GEAR NUMBER= 2

VELOCITY MET/S	GRADE	ERPM RPM	ACCEL MET/S/S	NHP HP	TR-EF KG	TIME S	DIST MET	FUEL LIT
8.01	0.0125	1291.753	-0.276	0.0	0.0	3.32	7.02	0.00542
8.51	0.0125	1184.840	1.076	62.6	1764.4	3.45	7.32	0.00590
9.01	0.0125	1256.566	1.085	66.9	1777.0	3.58	7.63	0.00641
9.51	0.0125	1328.293	1.094	71.2	1789.2	3.71	7.95	0.00694
10.01	0.0125	1400.019	1.102	75.5	1800.1	3.83	8.30	0.00750
10.51	0.0125	1471.746	1.100	79.3	1797.8	3.96	8.66	0.00808
11.01	0.0125	1543.472	1.098	83.0	1795.7	4.09	9.03	0.00868
11.51	0.0125	1615.199	1.093	86.6	1789.8	4.21	9.43	0.00931
12.01	0.0125	1686.925	1.077	89.5	1770.5	4.34	9.85	0.00997
12.51	0.0125	1758.652	1.063	92.3	1752.8	4.47	10.30	0.01067
13.01	0.0125	1830.378	1.048	95.1	1733.6	4.61	10.77	0.01141
13.51	0.0125	1902.105	1.031	97.6	1712.3	4.74	11.26	0.01219
14.01	0.0125	1973.831	1.016	100.1	1692.5	4.88	11.79	0.01300
14.51	0.0125	2045.557	0.998	102.4	1670.4	5.02	12.34	0.01386
15.01	0.0125	2117.284	0.980	104.5	1647.8	5.16	12.92	0.01475
15.51	0.0125	2189.010	0.964	106.7	1626.6	5.30	13.53	0.01569
16.01	0.0125	2260.737	0.938	107.9	1593.3	5.45	14.18	0.01668
16.51	0.0125	2332.463	0.911	109.0	1559.7	5.60	14.87	0.01773

GEAR UPSHIFT GEAR NUMBER= 3

VELOCITY MET/S	GRADE	ERPM RPM	ACCEL MET/S/S	NHP HP	TR-EF KG	TIME S	DIST MET	FUEL LIT
14.47	0.0125	1399.463	-0.283	0.0	0.0	7.60	23.47	0.01773
14.97	0.0125	1330.071	0.581	71.3	1126.9	7.84	24.45	0.01873
15.47	0.0125	1375.240	0.584	74.0	1131.3	8.08	25.45	0.01976
15.97	0.0125	1420.410	0.585	76.6	1133.2	8.32	26.49	0.02082
16.47	0.0125	1465.579	0.584	78.9	1132.3	8.55	27.56	0.02190
16.97	0.0125	1510.748	0.583	81.3	1131.4	8.79	28.67	0.02302
17.47	0.0125	1555.918	0.581	83.7	1130.6	9.03	29.81	0.02416
17.97	0.0125	1601.087	0.580	86.0	1129.7	9.27	30.99	0.02534
18.47	0.0125	1646.256	0.573	87.9	1121.7	9.51	32.22	0.02655
18.97	0.0125	1691.425	0.567	89.7	1114.2	9.76	33.49	0.02782
19.47	0.0125	1736.595	0.561	91.5	1107.1	10.01	34.81	0.02913
19.97	0.0125	1781.764	0.555	93.3	1100.4	10.26	36.18	0.03049
20.47	0.0125	1826.933	0.549	94.9	1092.4	10.51	37.61	0.03189
20.97	0.0125	1872.103	0.541	96.5	1083.8	10.77	39.08	0.03335
21.47	0.0125	1917.272	0.534	98.1	1075.6	11.03	40.61	0.03486
21.97	0.0125	1962.441	0.528	99.7	1067.8	11.29	42.20	0.03642
22.47	0.0125	2007.611	0.521	101.2	1059.9	11.55	43.85	0.03803
22.97	0.0125	2052.780	0.513	102.6	1050.5	11.83	45.56	0.03970
23.47	0.0125	2097.949	0.506	103.9	1041.4	12.10	47.33	0.04142
23.97	0.0125	2143.118	0.498	105.3	1032.8	12.38	49.16	0.04321
24.47	0.0125	2188.288	0.491	106.6	1024.5	12.66	51.07	0.04505
24.97	0.0125	2233.457	0.481	107.5	1011.8	12.95	53.05	0.04696

25.47	0.0125	2278.626	0.470	108.2	998.0	13.25	55.12	0.04895
25.97	0.0125	2323.736	0.459	108.9	984.7	13.55	57.29	0.05102
26.47	0.0125	2368.965	0.448	109.5	971.9	13.86	59.54	0.05317

GEAR UPSHIFT   GEAR NUMBER= 4

24.35	0.0125	1387.683	-0.295	0.0	0.0	15.86	73.66	0.05317
24.85	0.0125	1343.280	0.228	72.1	682.0	16.47	77.82	0.05575
25.35	0.0125	1370.585	0.229	73.7	683.6	17.07	82.05	0.05837
25.85	0.0125	1397.891	0.229	75.4	685.2	17.68	86.35	0.06103
26.35	0.0125	1425.197	0.228	76.8	685.0	18.29	90.76	0.06375
26.85	0.0125	1452.503	0.228	78.3	684.6	18.90	95.27	0.06651
27.35	0.0125	1479.808	0.227	79.7	684.3	19.51	99.88	0.06934
27.85	0.0125	1507.114	0.226	81.1	684.0	20.13	104.60	0.07221
28.35	0.0125	1534.420	0.225	82.6	683.7	20.75	109.43	0.07515
28.85	0.0125	1561.726	0.224	84.0	683.4	21.37	114.37	0.07813
29.35	0.0125	1589.031	0.223	85.4	683.1	21.99	119.41	0.08117
29.85	0.0125	1616.337	0.220	86.7	681.3	22.62	124.59	0.08429
30.35	0.0125	1643.643	0.217	87.7	678.4	23.26	129.93	0.08750
30.85	0.0125	1670.948	0.214	88.8	675.6	23.91	135.44	0.09080
31.35	0.0125	1698.254	0.212	89.9	672.9	24.56	141.11	0.09420
31.85	0.0125	1725.560	0.209	91.0	670.3	25.23	146.95	0.09770
32.35	0.0125	1752.866	0.206	92.1	667.8	25.90	152.96	0.10131
32.85	0.0125	1780.171	0.203	93.2	665.3	26.59	159.14	0.10501
33.35	0.0125	1807.477	0.200	94.3	662.7	27.28	165.51	0.10883
33.85	0.0125	1834.783	0.197	95.2	659.5	27.98	172.09	0.11276
34.35	0.0125	1862.089	0.194	96.2	656.3	28.70	178.88	0.11681
34.85	0.0125	1889.394	0.191	97.1	653.3	29.43	185.88	0.12098
35.35	0.0125	1916.700	0.187	98.1	650.3	30.17	193.10	0.12527
35.85	0.0125	1944.006	0.184	99.0	647.4	30.92	200.55	0.12970
36.35	0.0125	1971.311	0.181	100.0	644.6	31.69	208.23	0.13426
36.85	0.0125	1998.617	0.178	101.0	641.9	32.47	216.15	0.13895
37.35	0.0125	2025.923	0.175	101.8	638.4	33.26	224.33	0.14380
37.85	0.0125	2053.229	0.171	102.6	635.0	34.07	232.80	0.14880
38.35	0.0125	2080.534	0.168	103.4	631.6	34.90	241.57	0.15396
38.85	0.0125	2107.840	0.164	104.2	628.4	35.75	250.63	0.15929
39.35	0.0125	2135.146	0.161	105.1	625.2	36.61	260.00	0.16479
39.85	0.0125	2162.452	0.158	105.9	622.2	37.49	269.69	0.17046
40.35	0.0125	2189.757	0.154	106.7	619.1	38.39	279.70	0.17632
40.85	0.0125	2217.063	0.150	107.3	614.8	39.32	290.14	0.18241
41.34	0.0125	2244.266	0.145	107.7	609.6	40.18	300.00	0.18815
41.84	-0.0100	2271.469	0.351	108.1	604.6	40.58	304.58	0.19081
42.34	-0.0100	2298.775	0.346	108.5	599.7	40.98	309.27	0.19353
42.84	-0.0100	2326.080	0.341	108.9	594.9	41.38	314.09	0.19632

EAR UPSHIFT   GEAR NUMBER= 5

42.02	-0.0100	1443.775	-0.114	0.0	0.0	43.38	337.66	0.19632
42.52	-0.0100	1438.278	0.213	77.5	426.7	44.04	345.32	0.19925
43.02	-0.0100	1455.291	0.212	78.4	426.5	44.69	353.11	0.20223
43.52	-0.0100	1472.304	0.211	79.3	426.4	45.35	361.04	0.20525
44.02	-0.0100	1489.317	0.210	80.2	426.3	46.01	369.10	0.20832
44.52	-0.0100	1506.330	0.208	81.1	426.2	46.68	377.29	0.21143
45.02	-0.0100	1523.343	0.207	82.0	426.1	47.35	385.62	0.21459
45.52	-0.0100	1540.356	0.206	82.9	425.9	48.02	394.09	0.21779
46.02	-0.0100	1557.369	0.205	83.8	425.8	48.70	402.70	0.22104
46.52	-0.0100	1574.382	0.204	84.7	425.7	49.38	411.46	0.22433
47.02	-0.0100	1591.395	0.203	85.5	425.6	50.07	420.36	0.22767
47.52	-0.0100	1608.408	0.201	86.3	425.0	50.76	429.42	0.23107
48.02	-0.0100	1625.420	0.199	87.0	423.9	51.45	438.68	0.23454
48.52	-0.0100	1642.433	0.197	87.7	422.7	52.16	448.12	0.23807
49.02	-0.0100	1659.446	0.195	88.4	421.7	52.87	457.75	0.24168
49.52	-0.0100	1676.459	0.193	89.1	420.6	53.59	467.58	0.24535
50.02	-0.0100	1693.472	0.191	89.7	419.6	54.31	477.61	0.24910
50.52	-0.0100	1710.485	0.190	90.4	418.5	55.05	487.84	0.25293
51.02	-0.0100	1727.498	0.188	91.1	417.5	55.79	498.28	0.25682
51.52	-0.0100	1744.511	0.186	91.8	416.5	56.53	508.93	0.26080
52.02	-0.0100	1761.524	0.184	92.5	415.6	57.29	519.79	0.26486
52.52	-0.0100	1778.537	0.182	93.1	414.6	58.05	530.88	0.26900
53.02	-0.0100	1795.550	0.180	93.8	413.7	58.82	542.18	0.27321
53.52	-0.0100	1812.563	0.178	94.4	412.5	59.61	553.73	0.27752
54.02	-0.0100	1829.575	0.176	95.0	411.3	60.40	565.53	0.28192
54.52	-0.0100	1846.588	0.174	95.6	410.0	61.20	577.59	0.28640
55.00	-0.0100	1863.258	0.172	96.2	408.8	61.97	589.41	0.29080

ONSTANT SPEED

55.00	-0.0100	1871.421	0.000	43.9	185.7	96.05	1110.00	0.37877

NEXT SECTION PERCEPTION

54.46	0.0060	1862.304	-0.149	43.9	185.7	97.05	1125.20	0.38136
53.93	0.0060	1844.151	-0.148	43.9	185.7	98.05	1140.26	0.38394

53.41	0.0060	1826.155	-0.146	43.9	185.7	99.05	1155.17	0.38651
52.68	0.0060	1808.311	-0.145	43.9	185.7	100.05	1169.93	0.38908
52.37	0.0060	1790.618	-0.144	43.9	185.7	101.05	1184.55	0.39164
52.67	0.0060	1790.316	0.031	93.6	414.0	105.51	1249.76	0.41597
53.37	0.0060	1807.329	0.029	94.3	412.9	110.28	1320.12	0.44222
53.67	0.0060	1821.342	0.027	94.9	411.6	115.43	1396.84	0.47080
54.33	0.0060	1840.801	0.025	95.4	410.4	116.30	1410.00	0.47570
54.60	-0.0056	1856.604	0.131	96.0	409.3	116.30	1410.00	0.47570